

AD-A154 251

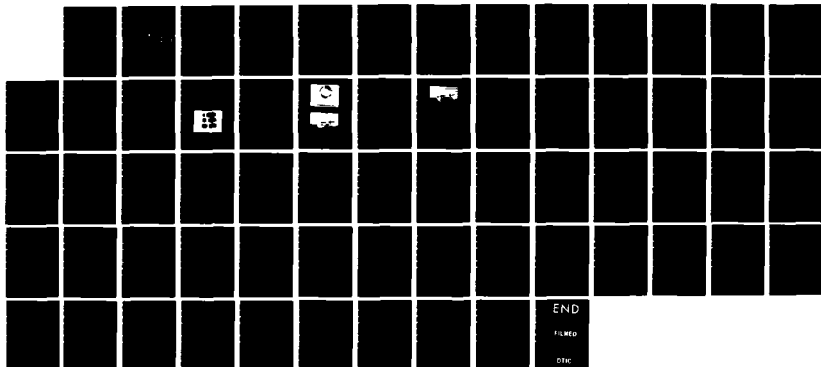
AN EXPERIMENTAL INVESTIGATION OF FUEL REGRESSION RATE
CONTROL IN SOLID FUEL RAMJETS(U) NAVAL POSTGRADUATE
SCHOOL MONTEREY CA B N KO DEC 84

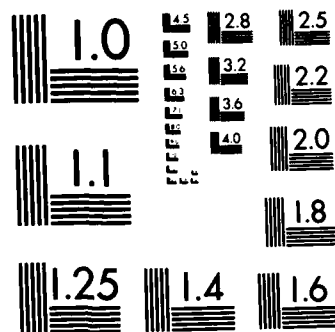
1/1

UNCLASSIFIED

F/G 21/2

NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

(2)

NAVAL POSTGRADUATE SCHOOL

Monterey, California

AD-A154 251



DTIC
ELECTE
MAY 30 1985
S B D

THESIS

AN EXPERIMENTAL INVESTIGATION
OF FUEL REGRESSION RATE CONTROL
IN SOLID FUEL RAMJETS

by

Ko, Bog Nam

December 1984

Thesis Advisor:

D. W. Netzer

Approved for public release; distribution is unlimited.

DTIC FILE COPY

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
	A154 251	
4. TITLE (and Subtitle) An Experimental Investigation of Fuel Regression Rate Control in Solid Fuel Ramjets		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; December 1984
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Ko, Bog Nam		8. CONTRACT OR GRANT NUMBER(s) N0001-84WR41049
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93943		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93943		12. REPORT DATE December 1984
		13. NUMBER OF PAGES 62
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution is unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Ramjet Solid Fuel Regression Rate Control		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) An experimental investigation was conducted to examine fuel regression rate control methods other than variable bypass air flow rates in the solid fuel ramjet. Air and oxygen injection at various axial locations within the fuel grain were examined as well as air, oxygen and ethylene injection through the step face. One inlet swirl design was also tested. Secondary gas injection was found to be inadequate for regression rate control. A small amount of inlet swirl resulted in a significant increase in fuel		

Regression rate, indicating that variable inlet swirl may be a viable technique for providing in-flight fuel flow rate modulation in the solid fuel ramjet.

Accession For	
NTIS CPA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
Distribution/	
Availability Codes	
Avail and/or	
Special	
A-1	

Approved for public release; distribution is unlimited.

An Experimental Investigation of Fuel Regression Rate Control
in
Solid Fuel Ramjets

by

Ko, Bog Nam
Major, Korea Army
B.S., Korea Military Academy, 1975
B.E., Yon' Sei University, Seoul Korea, 1980

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING SCIENCE

from the

NAVAL POSTGRADUATE SCHOOL
December 1984

Author:

KO, BOG NAM

Ko, Bog Nam

Approved by:

David W. Netzer

David W. Netzer, Thesis Advisor

Allen E. Fuhs

Allen E. Fuhs, Second Reader

M. F. Platzer

M. F. Platzer, Chairman,
Department of Aeronautics

J. N. Dyer

J. N. Dyer,
Dean of Science And Engineering

ABSTRACT

An experimental investigation was conducted to examine fuel regression rate control methods other than variable bypass air flow rates in the solid fuel ramjet. Air and oxygen injection at various axial locations within the fuel grain were examined as well as air, oxygen and ethylene injection through the step face. One inlet swirl design was also tested. Secondary gas injection was found to be inadequate for regression rate control. A small amount of inlet swirl resulted in a significant increase in fuel regression rate, indicating that variable inlet swirl may be a viable technique for providing in-flight fuel flow rate modulation in the solid fuel ramjet.

TABLE OF CONTENTS

I.	INTRODUCTION	10
II.	METHOD OF INVESTIGATION	14
	A. TEST CONDITITIONS AND METHODS	14
	B. DATA COLLECTION METHOD	15
III.	DESCRIPTION OF APPARATUS	24
	A. RAMJET MOTOR	24
	B. AIR SUPPLY SYSTEM	25
	C. AIR HEATER	28
	D. DATA ACQUISITION AND CONTROL SYSTEM	28
IV.	EXPERIMENTAL PROCEDURES AND TEST CONDITIONS . . .	30
	A. TRANSDUCER CALIBRATION	30
	B. FLOW RATES SET-UP	30
	C. TEST SEQUENCE	31
	1. Thrust Stand Calibration	31
	2. Fuel-wall Injection Tests	31
	3. Face Injection Tests	32
	4. Inlet Air Swirl Tests	32
V.	RESULTS AND DISCUSSION	33
	A. FUEL WALL INJECTION	33
	B. INLET STEP FACE INJECTION	34
	C. INLET AIR SWIRL	35
	D. THRUST STAND CALIBRATION	35
VI.	CONCLUSIONS AND RECOMMENDATIONS	42
	APPENDIX A: COMPUTER PROGRAM FOR EXPERIMENT CONTROL AND DATA REDUCTION	43
	LIST OF REFERENCES	60

INITIAL DISTRIBUTION LIST	61
-------------------------------------	----

LIST OF TABLES

1.	Fuel Wall Injection Results	37
2.	Step Face Injection Result	38
3.	Summary of Experimental Data	39

LIST OF FIGURES

1.1	Schematic of the SFRJ	11
2.1	Fuel Configurations for Side Wall Injection	15
2.2	Drawing of Injection Ring for Side Wall Injection	16
2.3	Injection Ring for Side Wall Injection	17
2.4	Step Insert For Gaseous Face Injection	17
2.5	Drawing of Step Insert for Gaseous Injection . . .	18
2.6	Swirl Element Inlet Injector	19
3.1	Schematic of the SFRJ Motor	26
3.2	Schematic of Air Supply System	27
3.3	Block Diagram of the Computer Data Aquisition/Control Program	29
5.1	Thrust Calibration Curve, Measured vs Actual . . .	41

ACKNOWLEDGEMENTS

I would like to express my deep appreciation to Professor David W. Netzer for his patience and assistance in completing this project. Thanks also to Mr. Pat Hickey and Mr. Glenn Middleton for their kindly assistance. Special thanks goes to my wife Gyung Gu and daughter Mee Seon and son Eugene for support and understanding during my stay at U.S Naval Postgraduate School.

I. INTRODUCTION

Ramjets operate with much higher specific impulse than rockets since ramjets use inlet air as a source of oxygen. Self-sufficient rockets, on the other hand, must carry their own oxidizer and bear the consequent penalty. Accordingly, although rockets must be chosen for propulsion outside of the atmosphere, and solid propellant rockets are unchallenged for short-range tactical applications, ramjets can generally outperform rockets in the medium and long range tactical environments.

Because the ramjet depends only on its forward motion at supersonic speeds to effectively compress intake air, the engine, in principle, can employ very few, if any, moving parts. It is therefore capable of simplicity, lightness of construction, and high flight speed not possible in other air-breathing engines. These features, plus the high thermal efficiency it can achieve, make the ramjet a particularly attractive choice for propelling vehicles at supersonic speeds.

One of the significant difference between rockets and ramjets is thrust at zero speed. Rockets can deliver thrust at any speed, whereas a ramjet requires an auxiliary boost system to accelerate it to its supersonic operating regime so that its forward motion can compress the inlet air. To operate at practical efficiency a ramjet must be moving at about a Mach number of 1.5 or greater so that the margin of thrust over drag will be satisfactory.

The solid fuel ramjet(SFRJ) employs solid fuel for the combustor walls. Its distinguishing feature is the absence of fuel tankage, fuel delivery, and fuel control systems. The solid fuel ramjet offers this simplicity while providing excellent density impulse and combustion efficiency.

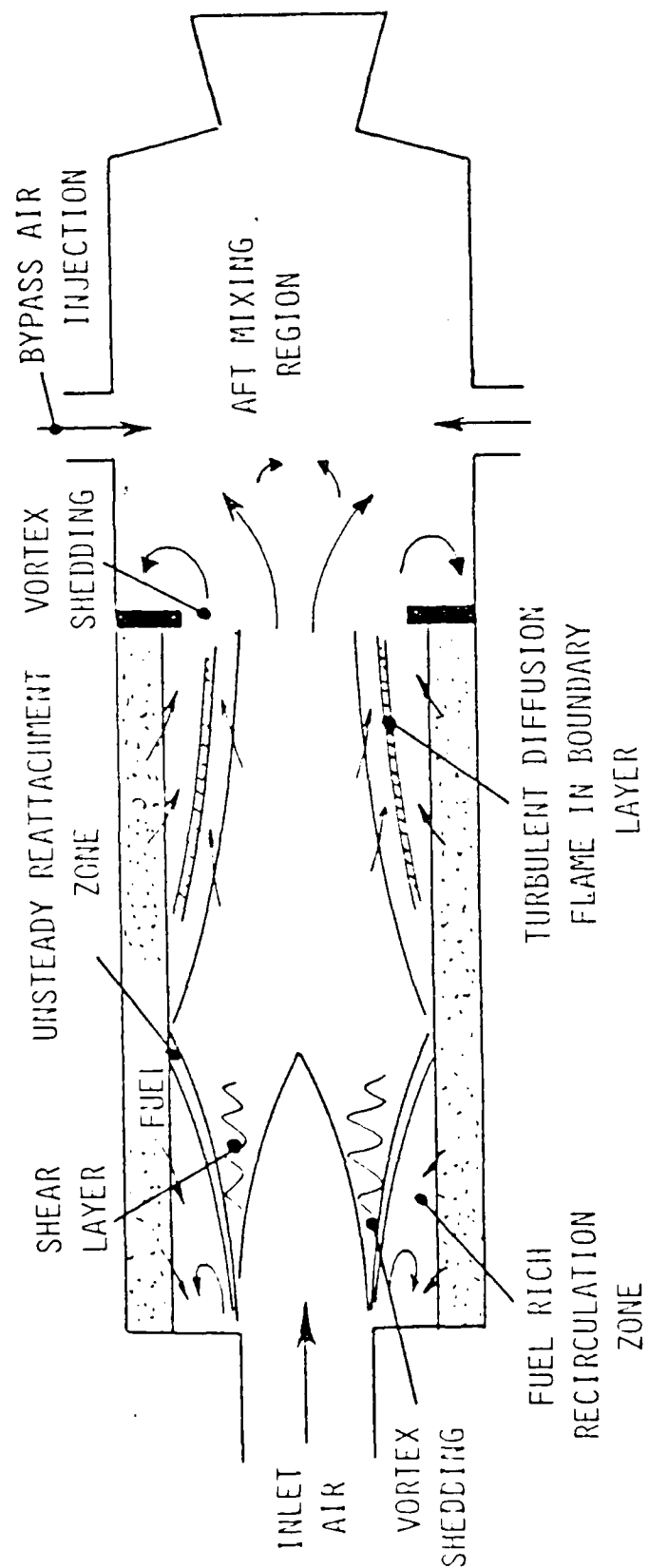


Figure 1.1 Schematic of the SFRJ.

flow was passed through a central swirl element which extended 0.5 inches into the combustor. The swirl was induced by machining six flutes with a twist of one turn in five inches. The latter resulted in an inlet swirl angle of approximately 5 degrees to the motor centerline.

During the normal ignition sequence, the air flow rate was set at the desired value before the ignition switch was activated. When the ignition circuit was activated, ethylene gas was introduced upstream of the fuel grain along with primary air flow. This mixture was ignited with an oxygen-ethylene torch which issued from the face of the step inlet. Normally, two to three seconds of ignition time was required for PMM combustion to sustain.

The step insert section was provisioned for variations in inlet diameters to make the sudden expansion. The fuel grain itself, when mounted in the motor, became the mid-body of the ramjet. The fuel grain (and injection ring, if used) mounted between the head-end assembly and the aft mixing chamber. The aft-mixing chamber had a length-to-diameter ratio of 2.9. The entire motor was held together by four threaded rods and nuts. The ramjet motor was then mounted on the thrust stand.

B. AIR SUPPLY SYSTEM

A schematic of the ramjet air supply system is shown in figure 3.2. From the air tanks, the air flows through a pressure regulator, a sonic choke, a vitiated air heater and finally to the head-end assembly. The air flow can be either vented into the atmosphere or vented through the ramjet motor by the control of two pneumatically operated valves. Two flexible air flow lines were used to connect the main air line to the air heater. The latter was mounted on the thrust stand.

III. DESCRIPTION OF APPARATUS

A. RAMJET MOTOR

The ramjet motor assembly used in this experiments was that used previously at NPS [Ref. 1, 2].

Figure 3.1 shows a schematic drawing of the ramjet, illustrating the main sections. These are, the head-end assembly, step insert section, fuel grain, aft mixing chamber and exhaust nozzle. For the tests with secondary injection, the injection ring was used.

The head-end assembly contains a central opening for the introduction of the primary air-flow, and ports for introduction of the ignition fuel and the igniter torch.

The fuel wall injection is shown in Figure 2.1, Figure 2.2 and Figure 2.3. Injection velocity varied between approximately 30 and 200 ft/sec as the injection mass flow rate was increased from 1% to 5 % of the inlet air flow. A nominal one dimensional flow port velocity was approximately 300 ft/sec.

For the face injection tests, air, oxygen or gaseous fuel was introduced using a differently designed step insert(Figure 2.4 and Figure 2.5). The injection was provided through eight equally spaced, 0.047 diameter holes. For an injection gas mass flow rate equal to 1 % of the inlet air flow rate the injection velocity was approximately 65 ft/sec.

To provide a swirl at the air inlet, a specially designed insert was used(Figure 2.6). This device was a tube-in-hole type injector. Approximately 43 % of the air flow passed through the outer annulus to maintain the recirculation region/flame holder. The other 57 % of the air

where P_e = exit pressure of the nozzle

P_o = ambient pressure. Then for a choked converging nozzle, this equation can be simplified to

$$C_{Fexp} = \sqrt{\left(\frac{2\gamma^2}{\gamma+1}\right)\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}} + \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} - \frac{P_o}{P_c}} \quad (2.13)$$

where R and γ are determined using PEPCODE

Then efficiency based on thrust is calculated from

$$\eta_{\Delta T_F} = \frac{C_{exp}^{*2} - C_a^{*2}}{C_{th}^{*2} - C_a^{*2}} \quad (2.14)$$

where C_{exp}^* = $\bar{F} g_c / (\dot{M}_t C_{Fexp})$

C_a^* = $\bar{F} / (\dot{M}_{pi} C_F)$ (determined before

ignition)

\bar{F} = average thrust from analog

record

\dot{M}_{pi} = pre-ignition flow rate

$$D_{th} = \sqrt{\frac{C_{air}^* \dot{m}_{air}}{P_c \frac{\pi}{4} g_c}} \quad (2.8)$$

Then temperature-rise combustion efficiency based on nozzle stagnation pressure can be calculated using c^*

$$\eta_{\Delta T_p} = \frac{C_{exp}^{*2} - C_a^{*2}}{C_{th}^{*2} - C_a^{*2}} \quad (2.9)$$

where C_a^* = characteristic exhaust velocity for air flow before ignition

C_{exp}^* = experimental characteristic exhaust velocity based on P_c , the average combustion pressure

C_{th}^* is obtained from equation (2.7) using γ , R and T_t from PEPCODE with inputs of P_c , T_a , \dot{m}_{air} , \dot{m}_f , \dot{m}_{O_2} and $\dot{m}_{C_2H_4}$. The latter two flow rates are used in the vitiated air heater.

The thrust equation is

$$F = \dot{m}_t U_e + (P_e - P_o) A_e \quad (2.10)$$

$$\text{where } \dot{m}_t = \dot{m}_{air} + \dot{m}_f + \dot{m}_{O_2} + \dot{m}_{C_2H_4}$$

A thrust coefficient, C_F , can be defined such that

$$F = C_F P_t A_{th} \quad (2.11)$$

$$C_{F_{exp}} = \sqrt{\left(\frac{2\gamma^2}{\gamma-1}\right) \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}} \left\{1 - \left(\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{\gamma}}\right\} + \left(\frac{P_e - P_o}{P_c}\right) \frac{A_e}{A_{th}}} \quad (2.12)$$

based on thrust. The one dimensional continuity equation ($\dot{m} = \rho A V$) can be expressed in terms of the chamber stagnation properties for a choked converging nozzle

$$\dot{m}_t = \frac{P_t A_{th_{eff}}}{\sqrt{R T_t}} \sqrt{g_c \gamma \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \quad (2.5)$$

where \dot{m}_t = total flow rate

$P_t = P_c$, chamber pressure (for low Mach number)

$A_{th_{eff}}$ = effective nozzle throat area

R = gas constant

The characteristic exhaust velocity, c^* is defined as

$$c^* = \frac{P_c A_{th} g_c}{\dot{m}_t} = \frac{F g_c}{C_F \dot{m}_t} \quad (2.6)$$

where C_F = thrust coefficient

For a sonically choked exhaust nozzle,

$$c^* = \sqrt{\frac{g_c}{\gamma} \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}} R T_t} \quad (2.7)$$

Using pre-test air flow through the motor, equations (2.6) and (2.7) can be used to determine the effective exhaust nozzle throat diameter ($D_{th_{eff}}$)

$$\overline{D_f} = \sqrt{\frac{4 \Delta W}{\pi \rho L} + \overline{D_i}^2} \quad (2.2)$$

where ΔW = weight change

L = length of the fuel grain

ρ = density of the fuel grain

$\overline{D_i}$ = average initial port diameter of the PMM grain

The average fuel regression rate was then computed using

$$\dot{r}_{avg} = \frac{\overline{D_f} - \overline{D_i}}{2 t_b} \quad (2.3)$$

The mixture ratio, chamber pressure and motor air inlet temperature were used as input into the Naval Weapons Center(NWC) China Lake, Ca., Propellant Evaluation Program(PEPCODE) computer program to obtain the theoretical adiabatic combustion temperature and the combustion gas properties(γ and R). This temperature was used to calculate temperature rise combustion efficiencies based on thrust and based on nozzle stagnation pressure, where

$$\eta_{\Delta T} = \frac{T_{texp} - T_a}{T_{tth} - T_a} \quad (2.4)$$

and T_{texp} = combustor stagnation temperature

T_{tth} = theoretical combustor temperature

T_a = inlet air temperature

Experimental values of combustor stagnation temperatures were calculated in two ways, one based on pressure and one

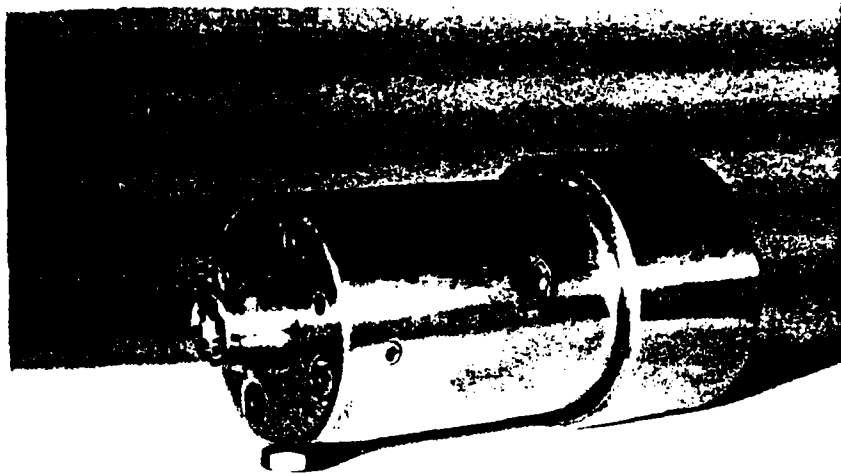


Figure 2.6 Swirl Element Inlet Injector.

Temperatures were only recorded digitally. Average values of the thrust and chamber pressure were determined using a compensating polar planimeter on the analog record.

The mass flow rate of air was obtained by using sonically choked nozzles. Average fuel mass flow rate was calculated by using the weight loss during the burn time

$$\dot{M}_f = \frac{\Delta W}{t_b} \quad (2.1)$$

where ΔW = weight change during the run
 t_b = burn time

The average internal diameter of the fuel grain was measured prior to the run. The final average diameter was determined based on weight loss and fuel length by using

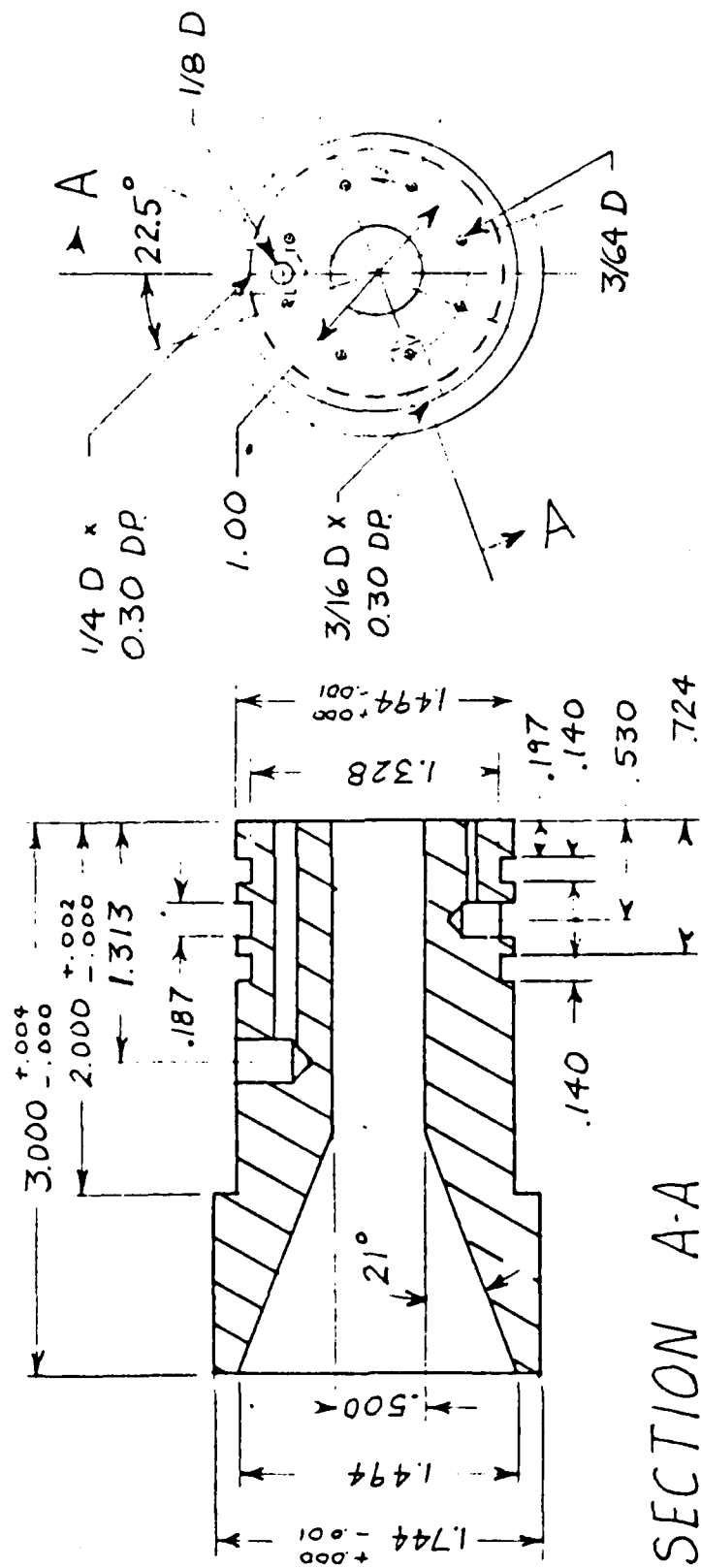


Figure 2.5 Drawing of Step Insert for Gaseous Injection.

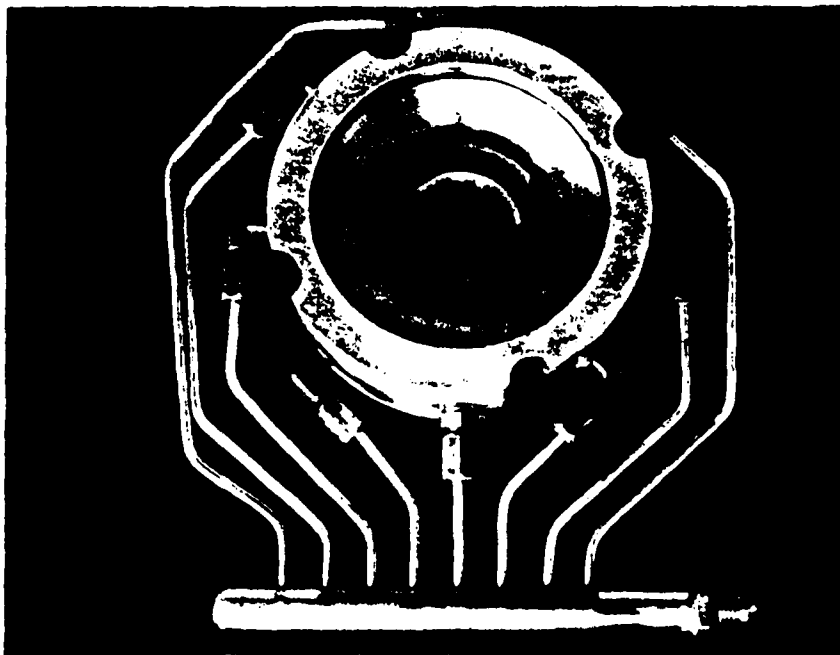


Figure 2.3 Injection Ring for Side Wall Injection.

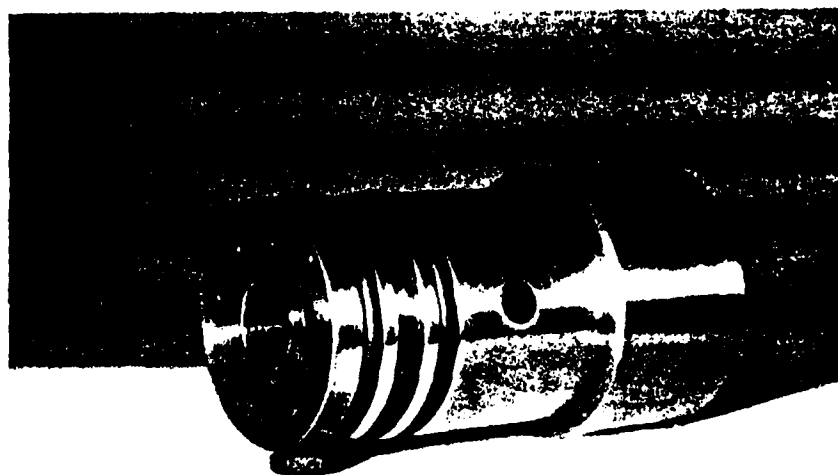


Figure 2.4 Step Insert For Gaseous Face Injection.

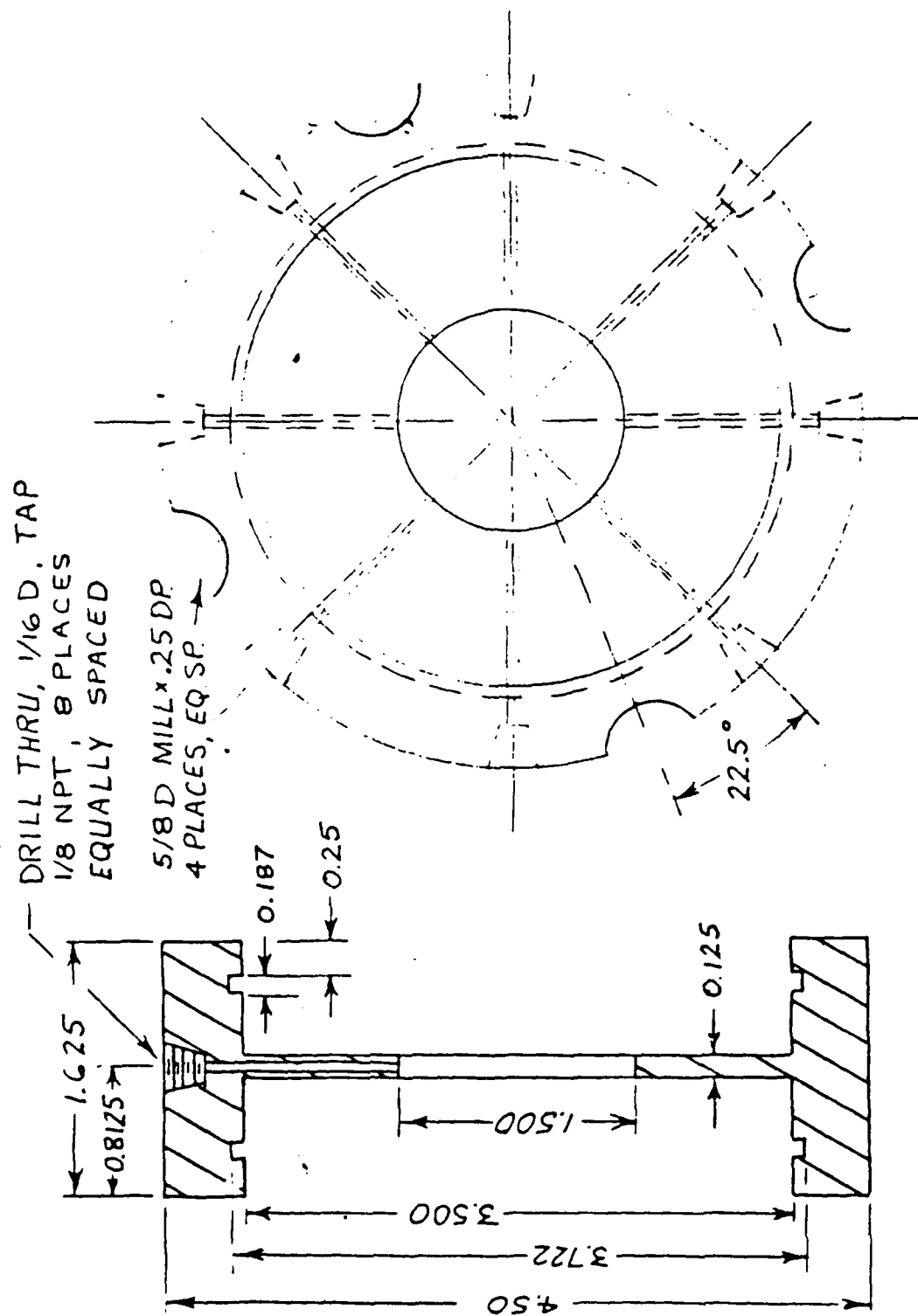


Figure 2.2 Drawing of Injection Ring for Side Wall Injection.

conditions found to significantly affect chamber pressure(or thrust) were further evaluated using full-length burn times of approximately 30 seconds (in order to accurately determine regression rate and combustion efficiency).

B. DATA COLLECTION METHOD

The data collected during the regression rate control tests consisted of air flow rates, oxygen, air or fuel flow rates for the injection, motor head-end and chamber pressures, weight changes of the fuel grain, pre-ignition air flow time, ignition time, burning time, purge time, thrust and ignition gas flow rate. All pressures and the thrust were recorded both digitally and analog.

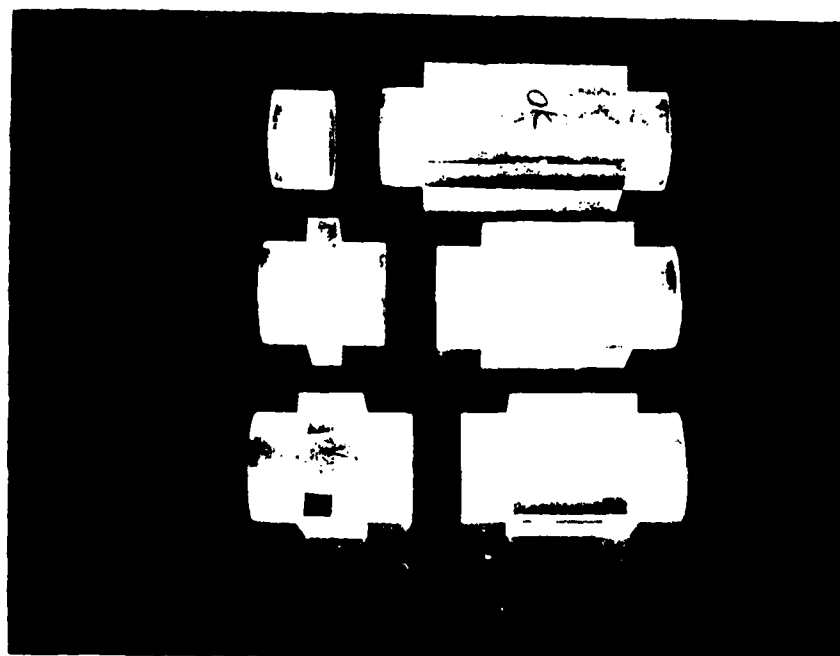


Figure 2.1 Fuel Configurations for Side Wall Injection.

II. METHOD OF INVESTIGATION

A. TEST CONDITIONS AND METHODS

The experimental investigation was begun by selecting several configurations for regression rate control through the utilization of secondary injection. It was decided to examine secondary injection at three locations through the fuel grain wall: in the recirculation zone(flame holder area), just downstream of flow reattachment and further downstream within the region of the developing boundary layer (in which is located a turbulent diffusion flame). In addition, gaseous injection on the inlet step face and inlet air swirl were examined.

Polymethylmethacrylate(PMM) was used as the fuel and had a nominal length of 12 inches and an internal diameter of 1.5 inches. A sudden expansion inlet was used which provided an inlet step height of 0.49 inches.

Flow reattachment normally occurs between 7 and 8 step heights(i.e, 3.5 - 4 inches). Thus the three injection location chosen where 2, 5, and 8 inches from the head end(See Figure 2.1).

The injection ring was designed to provide radial injection through eight equally spaced, 0.0625 inches diameter holes(See Figure 2.2 and Figure 2.3).

Gaseous injection was also used through the inlet step face as shown in Figure 2.4 and Figure 2.5.

Swirl was provided to the inlet air flow through the use of a swirl element inlet injector(Figure 2.6).

Initial screening tests of short duration were made in which no injection or swirl was used, followed by tests with various amounts of gaseous injection or swirl. Those

oscillations. Therefore, other fuel regression rate control techniques should be pursued.

One possible alternative technique is the use of variable swirl at the air inlet. Increased swirl may increase the regression rate. This technique would require a vane control device. Another possibility is the use of secondary injection of air, oxygen or gaseous fuel into one or more locations within the combustor. This may lead to both increased fuel regression rate and combustion efficiency. If oxygen were used it would require an auxillary supply system. Therefore, it would be a practical possibility (to maintain simplicity) for a one-time augmentation in thrust(at take-over from booster, at terminal maneuver, etc).

In this investigation tests were conducted to examine the effects of secondary gaseous injection and inlet air swirl on regression rate and combustion efficiency.

A new ramjet thrust stand was installed in the combustion laboratory and required calibration and certification. A second part of this investigation was to conduct tests using high temperature inlet air and then to ensure that combustion efficiencies based on thrust and based on measured chamber pressure were in agreement.

Fig 1.1 shows a schematic of a SFRJ combustor. One inherent problem with the SFRJ is the dependence of fuel regression on the air mass flux through the fuel grain. The fuel regression rate generally behaves according to

$$\dot{r} = k \left(\frac{\dot{M}_{air}}{A_p} \right)^x f(T_{air}, P) \quad (1.1)$$

where \dot{r} = fuel regression rate

\dot{M}_{air} = air flow rate

A_p = port area

$f(T_{air}, P)$ = a weaker function of inlet air temperature and pressure

x is between .3 and .6

If the air flow rate increases or decreases, then the fuel flow rate varies in the correct direction, but not enough to maintain design fuel-air ratio. This can significantly affect propulsive thrust.

The range of application and the performance of the SFRJ could be significantly improved if fuel regression rate could be controlled in some manner. Perhaps the most obvious method for fuel regression rate control is to use variable bypass air flow.

Bypass designs are often desired in order to increase fuel loading, and can also improve combustion efficiency. A valve in the bypass line could be used to vary the bypass ratio, thus producing changes in the fuel flow rate according to equation 1.1. (since only the fuel port air mass flux affects the regression rate). However, combustion efficiency may vary significantly with the amount of bypass air and a control valve must be used in the inlet air ducting. In addition, flow coupling may lead to undesired

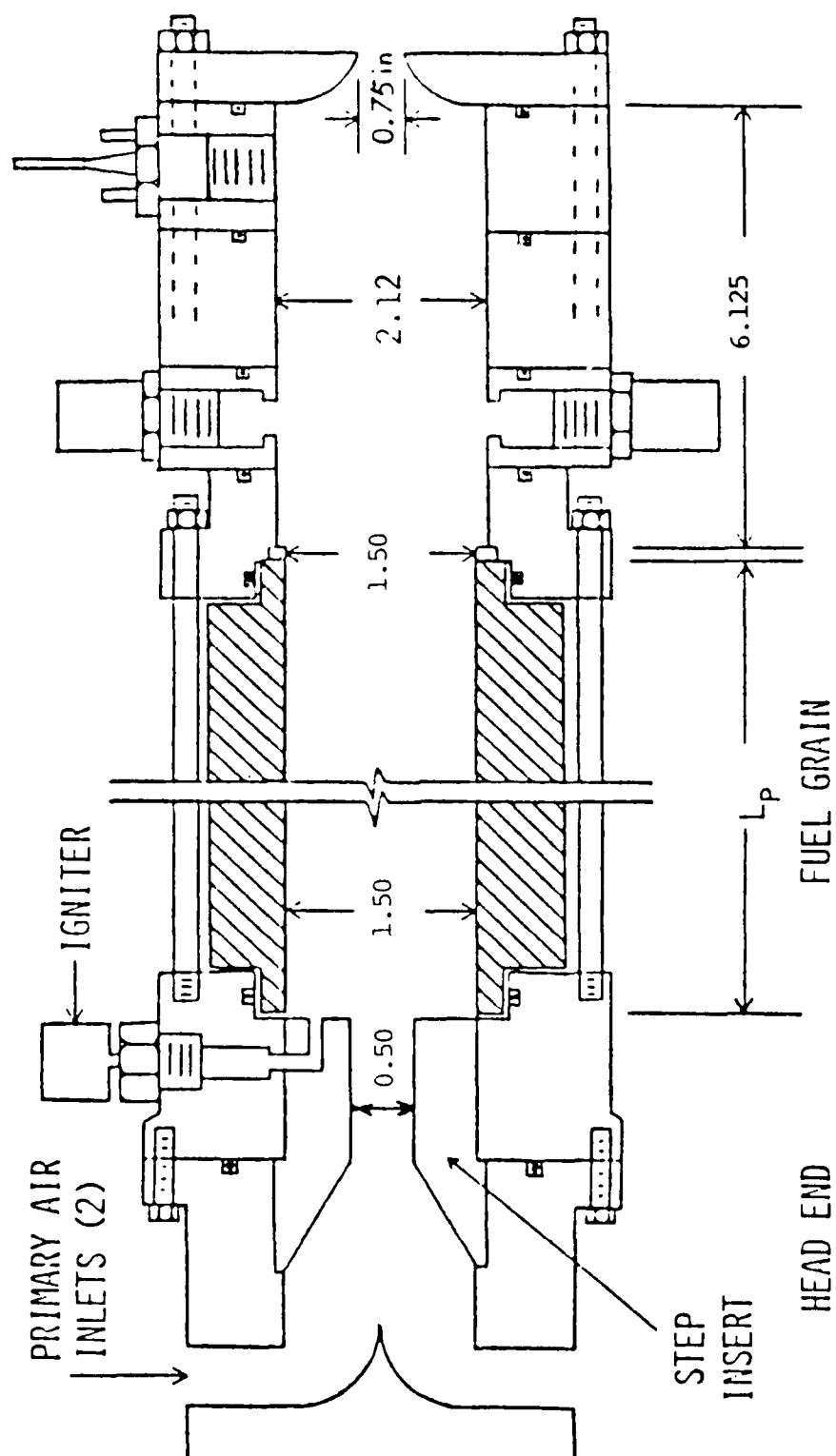


Figure 3.1 Schematic of the SFRJ Motor.

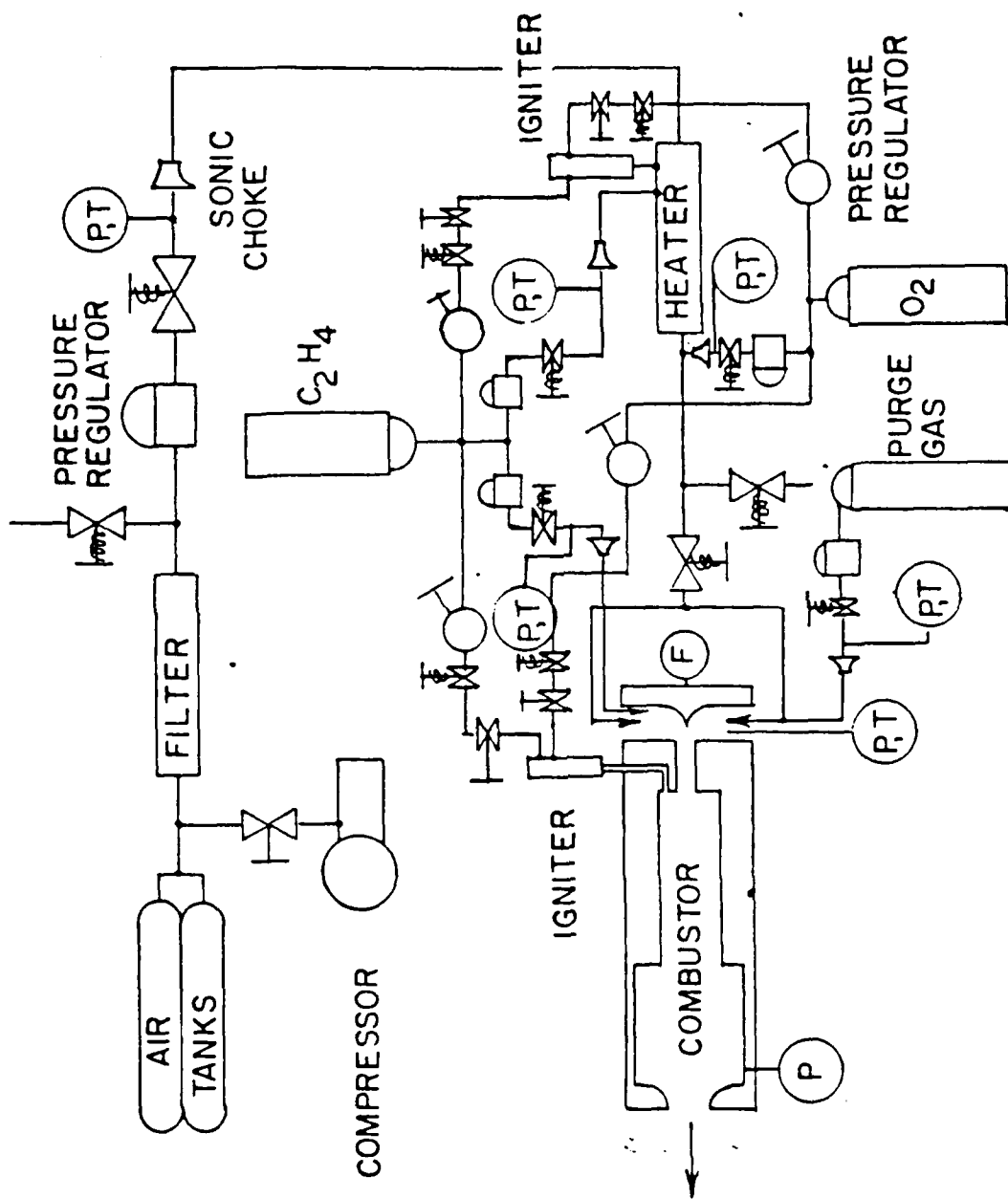


Figure 3.2 Schematic of Air Supply System.

C. AIR HEATER

To simulate actual flight condition, air should be heated to the appropriate stagnation temperature. In this investigation ethylene gas used in the air heater. The oxygen in the air which is consumed during the heating must be replaced before injection into the ramjet combustor. Figure 3.2 shows a schematic diagram of the air heater. The air heater and the ramjet motor assembly were mounted together on the thrust stand.

D. DATA ACQUISITION AND CONTROL SYSTEM

The primary instrumentation used in this investigation consisted of various individual pressure transducers and thermocouples and a strain gage load cell for the thrust measurement. All transducer outputs were recorded both with a Honeywell 1508 Visicorder and HP-9836S computer using a HP-3054A AUTOMATIC DATA ACQUISITION/CONTROL SYSTEM. A timing reference signal was provided to the analog record by feeding a 10 Hz signal from a laboratory signal generator to the timing channel of the Visicorder. During the test, the HP-9836S computer system was used to record the temperatures, and thrust, and calculate the flow rates of the ignition gas, purge gas, air heater ethylene and oxygen, air and secondary injection gas. It was necessary to record the PMM fuel grain weight and inner diameter before and after each run. The fuel grain weight was measured using a balance. All thermocouples used were chromel vs alumel (type K) with electronic ice points.

The computer was used to both control the test sequence and to provide data acquisition during the experiment. Figure 3.3 is a block diagram of the computer program. (See Appendix A. for a complete listing). Data acquisition for all fourteen channels were recorded every 0.5 seconds.

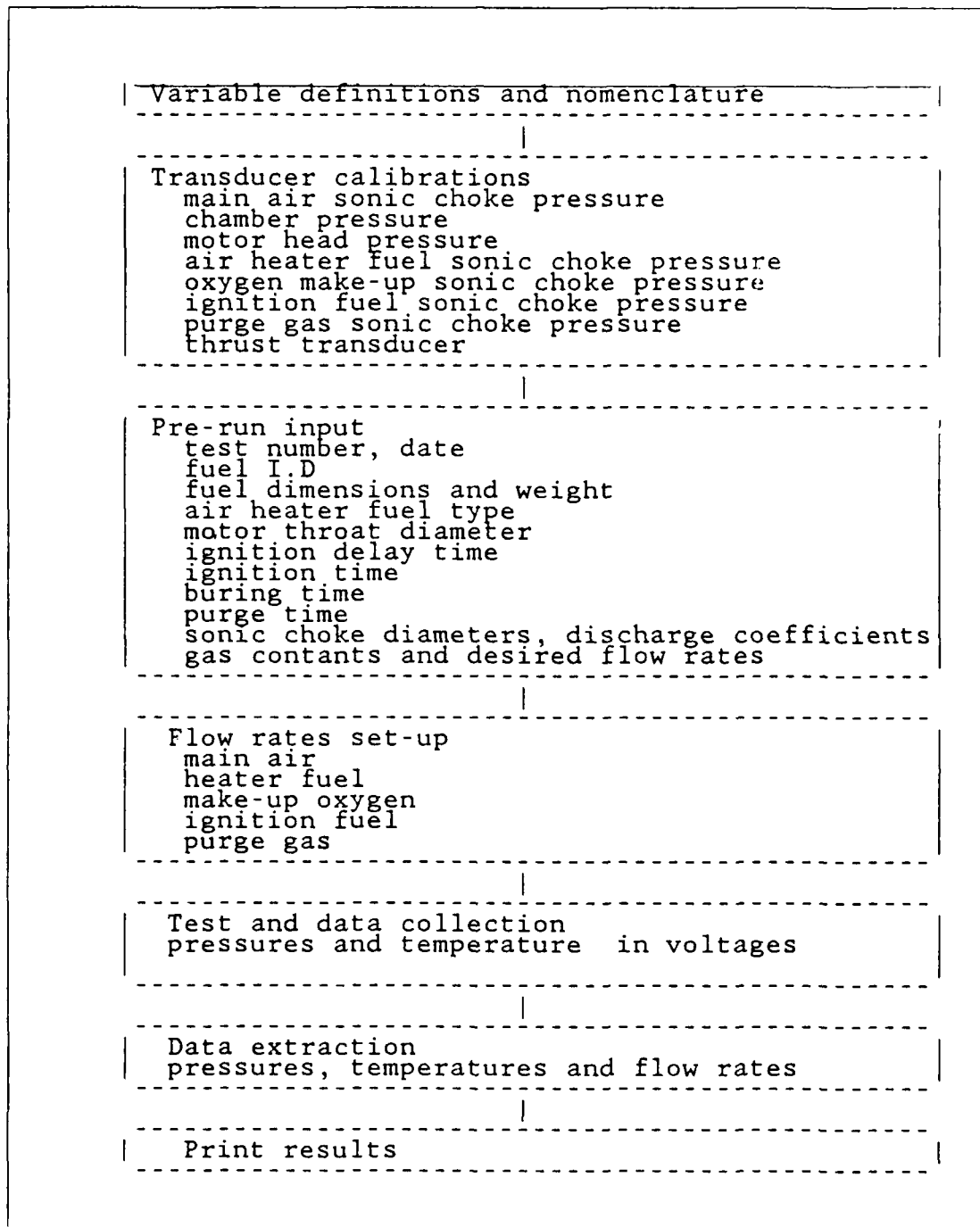


Figure 3.3 Block Diagram of the Computer Data Acquisition/Control Program.

IV. EXPERIMENTAL PROCEDURES AND TEST CONDITIONS

A. TRANSDUCER CALIBRATION

A dead-weight tester was used for the calibration of all pressure transducers. Initially all transducers were checked for linearity and the Visicorder(analog) display positions were labeled. For the computer data aquisition, voltages corresponding to atmospheric pressure and the maximum pressure were measured. From these readings a calibration constant (K) was determined for each transducer.

$$K = \frac{V_{pmax} - V_{p0}}{P_{max}} \quad (4.1)$$

where V_{pmax} = voltage reading at the applied maximum pressure

V_{p0} = voltage reading at atmospheric pressure

P_{max} = maximum applied pressure

The thrust transducer was calibrated in-place by applying known weights to the transducer through a pulley system attached to the thrust stand.

B. FLOW RATES SET-UP

By use of the computer, the gas flow rates could be set up before the hot firing. These were determined from short duration flows using the equation

$$\dot{M} = \frac{C_d K_m P_t \frac{\pi}{4} D_{choke}^2}{\sqrt{T_t}} \quad (4.2)$$

where k_m = constant (a function of R and γ)

C_d = discharge coefficient

P_t = total pressure of the gas flow

D_{choke} = sonic choke diameter

T_t = total temperature of the gas flow

C. TEST SEQUENCE

1. Thrust Stand Calibration

The thrust stand was calibrated to determine the difference between the measured thrust and the actual or theoretical thrust. The measured thrust can be in error primarily due to the variation in flex-line stiffness with changing pressure levels. The process was begun by dead-weight calibration of the load cell. Cold air was then flowed through the motor with a choked exhaust nozzle. Measured thrust was recorded and compared to the theoretical thrust. The latter was calculated using Equations (2.11) and (2.13). This was repeated for increasing air flow rates and for three different exhaust nozzle throat diameter. An additional test was made using hot air (1200° R) and a 12 inches long HTPB fuel grain. This test was conducted in order to compare the temperature rise combustion efficiency determined by using chamber pressure and by using thrust.

2. Fuel-wall Injection Tests

For the fuel-wall injection tests, three injection location were used as discussed above. Each test lasted for approximately six seconds, three seconds without injection

and three seconds with injection. Air injection mass flows of 2, 5 and 7 percent of the main air flow rate were used. For oxygen injection, 1.5, 2 and 5 percent were used. Those conditions which resulted in the greatest increases in chamber pressure/thrust were repeated with full duration(30 sec) tests.

3. Face Injection Tests

In these experiments a twelve inches long cylindrically perforated PMM fuel grain was used. Air injection flow rates of 2, 5 and 7 percent of the main air flow rate were examined. For oxygen injection, 1.5, 2 and 5 percent were used. Ethylene was also used with 0.5, 1.25 and 2.5 percent. Testing methods were identical to those discussed above for fuel-wall injection.

4. Inlet Air Swirl Tests

Several inlets were initially tried which induced swirl to the entire inlet air flow. Swirling the entire flow apparently destroys the flameholding recirculation zone, and resulted in no ignition. The tube-in-hole injector discussed above was then tested using a twelve inch PMM fuel grain.

V. RESULTS AND DISCUSSION

Summaries of the experimental results obtained during the initial screening tests are presented in Table 1 and Table 2 for fuel-wall and inlet step-face injection respectively. Results from the subsequent full duration tests are presented in Table 3.

A. FUEL WALL INJECTION

In data presented in Table 1 shows that air injected through the fuel grain surface was generally detrimental to combustion. Air injection rates up to approximately 7 % of the inlet air flow rate had little if any effects on combustion pressure when introduced downstream of flow reattachment. Small amounts of air injected into the recirculation zone appeared to provide small improvements. The injected air was quite cold (approximately 500°R) and therefore could have had a quenching effect on the boundary layer combustion. Use of "in-flight" high air should be examined in the future.

Unheated oxygen injection resulted in significant increases in combustion pressure, especially when introduced into the recirculation zone in small amounts. Based on these screening test results two additional tests were conducted with test times of approximately 30 seconds. These tests were made to examine the effects of 1 % oxygen injection into the recirculation region.

In these tests, a total grain length of fourteen inches was used; two inches of PMM, then the injection ring and then twelve inches of PMM. One test (Table 3, no. 30) was made without injection and one with (Table 3, no. 29).

Oxygen injection resulted in approximately a 5 % increase in fuel regression rate (when adjusted for the different air flowrate) but a decrease of 21 % in combustion efficiency. The recirculation zone is generally fuel rich. Thus, oxygen injection should increase the "flame-holder" temperature. This was evident during the test from increased flame luminosity.

It is not clear at this point why the combustion efficiency decreased or, for that matter, why the presence of the ring alone increased combustion efficiency. The oxygen injection velocity was approximately 30 ft/sec which is less than 30 % of typical recirculation zone, near-wall velocities. However, the injected oxygen may have penetrated the shear layer.

Further testing would be beneficial, especially using HTPB, but at this point it does not appear that fuel wall injection of small amounts of air or oxygen is a viable method for providing fuel mass flowrate control since combustion efficiency was decreased significantly and the increase in regression rate was small.

B. INLET STEP FACE INJECTION

The data from the screening tests with step-face injection are presented in Table 2. Unheated air had no significant effect on combustion pressure. Oxygen injection resulted in increased flame luminosity in the recirculation zone but apparently did not significantly affect downstream combustion (even though the overall equivalence ratio was approximately 0.7). Injection of ethylene resulted in significant increases in combustion pressure.

A full duration test (Table 3, no. 28) was conducted using 1 % of ethylene with an injection velocity of approximately 65 ft/sec. Comparison of the results with

those for no injection (Table 3, no. 27) showed that only a small increase occurred in fuel regression rate.

Some of the ethylene apparently escaped the recirculation region and burned downstream in the central air or in the aft mixing region, resulting in little effect on regression rate.

C. INLET AIR SWIRL

Only one test was conducted using inlet air swirl (Table 3, no. 31). Approximately 43 % of the air was injected axially to maintain the recirculation zone flame holding ability. This could be reduced to perhaps only 10 - 20 %, resulting in more air with swirl. The amount of swirl was also intentionally kept small (5 degrees from the axial direction) to determine if regression rate was sensitive to the swirl.

The small amount of swirl increased the fuel regression rate by 15 %. This resulted in an increase in equivalence ratio from 0.69 to 0.79 . Some non-uniformity in regression rate was also evident.

These initial results indicate that fuel regression rate is quite sensitive to inlet air swirl. Further testing is necessary using varying amounts of swirl, but the technique appears viable for in-flight fuel mass flow modulation.

D. THRUST STAND CALIBRATION

The results from the cold-flow tests for comparison of measured and calculated thrust are in Figure 5.1. Excellent agreement was attained. A least-square fit of the data resulted in the following equation for relating measured thrust to the "actual" thrust

$$F_a = 1.0149 \times F_m + 0.4 \quad (5.1)$$

where F_a = actual thrust, based on P_c and throat diameter

F_m = measured thrust

A test was then conducted (Table 3, no. 32) in which HTPB fuel was used with an inlet air temperature of approximately 1200 R. This test was made in order to compare the combustion efficiencies based on chamber pressure and based on thrust. The two efficiencies were within 5 %, with the value based on P_c being greater. This difference is not large when it is realized that small errors in determining F and P_c from the analog traces are squared when calculating C for the efficiency based on thrust determination.

TABLE 1
Fuel Wall Injection Results

test number	Mair (Lbm/sec)	Minj (Lbm/sec)	Minj/Mair %	$\Delta P_c/P_c$ %	Injected gas
8 inches and 4 inches configuration					
1	0.192	0.004	2.1	0	air
2	0.193	0.0029	1.5	0	air
3	0.205	0.0042	2.1	0	air
4	0.202	0.014	6.9	5.0	air
5	0.196	0.014	7.1	5.0	air
6	0.200	0.001	0.5	1.6	oxygen
7	0.197	0.002	1.0	3.3	oxygen
8	0.192	0.0039	2.0	3.4	oxygen
9	0.197	0.004	2.0	3.7	oxygen
5 inches and 7 inches configuration					
10	0.202	0.01	4.95	3.5	air
11	0.208	0.001	0.48	1.7	oxygen
12	0.202	0.003	1.5	3.3	oxygen
2 inches and 10 inches configuration					
13	0.200	0.004	2.0	3.3	air
14	0.200	0.01	5.0	5.1	air
15	0.205	0.01	5.0	2.5	oxygen
16	0.209	0.0011	0.54	2.5	oxygen
17	0.182	0.0033	1.8	4.4	oxygen
18	0.198	0.0038	1.9	4.6	oxygen

TABLE 2
Step Face Injection Result

Test number	\dot{M}_{air} (Lbm/sec)	\dot{M}_{inj} (Lbm/sec)	$\dot{M}_{inj}/\dot{M}_{air}$ %	$\Delta P_c/P_c$ %	Injected gas
19	0.196	0.003388	2.0	3.0	air
20	0.201	0.0104	5.0	4.0	air
21	0.209	0.00099	0.5	0.0	oxygen
22	0.143	0.00095	0.65	0.0	oxygen
23	0.205	0.00105	0.5	4.0	ethylene
24	0.201	0.00264	1.25	5.9	ethylene
25	0.203	0.00513	2.5	5.0	ethylene

TABLE 3
Summary of Experimental Data

Test number	27	28	29	30	31	32
Condition	nominal	1 % C ₂ H ₄ face injection	1 % O ₂ recircul- ation zone	same as 29 with- out inje- ction	inlet air swirl	nominal
Fuel	PMM	PMM	PMM	PMM	PMM	HTPB
Initial weight (Lbm)	6.01	6.035	6.645	6.013	5.583	1.664
Final weight (Lbm)	5.448	5.471	5.972	5.410	5.169	1.165
Length (in)	11.933	11.848	13.838	14.013	11.761	12.170
Dp, intial (in)	1.500	1.502	1.501	1.503	1.502	1.538
D _{thet} † (in)	0.739	0.739	0.737	0.744	0.737	0.938
Fuel Density (Lbm/cu.in)	0.0426	0.0426	0.0426	0.0426	0.0426	0.0332
f stoichiometric	0.121	0.121	0.121	0.121	0.121	0.0737
Burn time (sec)	33.1	33.1	33.4	33.1	34.3	9.9
M _{air} (Lbm/sec)	0.203	0.202	0.203	0.185	0.202	0.498
T _{air, inlet} (R)	546	538	501	563	504	1172
M _f (Lbm/sec)	0.0169	0.0171	0.0201	0.0182	0.0194	0.0504
ṙ (in/sec)	0.0062	0.0063	0.00634	0.0058	0.0071	0.0225

```

6550 ENTER 722;Vphf
6560 OUTPUT 709;"AC10"
6570 OUTPUT 722;"T3"
6580 ENTER 722;Vthf
6590 CLEAR 709
6600 OUTPUT 709;"DC10,0"
6610 PRINT "MANUALLY TURN OFF AIR 'HEATER GAS' SWITCH"
6620 BEEP
6630 DISP "HIT CONTINUE TO PROCEED"
6640 PAUSE
6650 OUTPUT 709;"DO10,0"
6660 Phf=(Vphf-Vphf0)*Kphf+Pbar
6670 Volts=Vthf
6680 GOSUB Tcalc
6690 Thf=T
6700 Mhf=Kmhf*Cdhf*Phf*.7854*(Dhfchoke^2)/(Thf^.5)
6710 PRINT USING "Q"
6720 PRINT USING "4A,DD.DDDDD";"Mhf=";Mhf
6730 PRINT USING "12A,DD.DDDDD";"Mhf DESIRED=";Mhfd
6740 Ratio=Mhf/Mhfd
6750 PRINT USING "18A,D.DDD,2X,4A,DDDD.DD,1A";"Mhf/ Mhf DESIRED=";Ratio,"Thf=";Thf,"R"
6760 Pq=Phf-Pbar
6770 PRINT USING "5A,DDDD.DDD,4A,3X,4A,DDDD.DD,1A,4A,DDDD.DD,1A";"Phf=";Pq;"P
sig","Thf=";Thf;"R"
6780 INPUT "IS HEATER FUEL FLOW RATE ACCURATE ENOUGH? (Y/N)",Xx$
6790 IF Xx$="Y" THEN GOTO Phffin
6800 Phfnew=(Phf*Mhfd/Mhf)-Pbar
6810 PRINT USING "13A,DDDD.DD,4A";"RESET Phf TO";Phfnew;"Psig"
6820 DISP "HIT CONTINUE AFTER RESET OF Phf"
6830 PAUSE
6840 GOTO Phfset
6850 Phffin:
6860 DISP "HIT CONTINUE TO PROCEED TO NEXT FLOW RATE SET UP"
6870 PAUSE
6880 Phfskip:
6890 PRINT USING "Q"
6900 INPUT "DO YOU WANT TO PRESET THE HEATER OXYGEN FLOW RATE?(Y/N)",Zz$
6910 IF Zz$="N" THEN GOTO Phoskip
6920 *****
6930 PRINT "SET THE DESIRED VALUE OF Pho USING THE HAND LOADER/PRESSURE GAGE"
6940 *****
6950 DISP "HIT CONTINUE WHEN READY"
6960 PAUSE
6970 Phoset:
6980 PRINT "MANUALLY TURN ON AIR 'HEATER GAS' SWITCH"
6990 DISP "HIT CONTINUE TO PROCEED"
7000 PAUSE
7010 OUTPUT 709;"AC4"
7020 OUTPUT 722;"T3"
7030 ENTER 722;Vpho
7040 OUTPUT 709;"AC11"
7050 OUTPUT 722;"T3"
7060 ENTER 722;Vtho
7070 CLEAR 709
7080 OUTPUT 709;"DC10,0"
7090 PRINT "MANUALLY TURN OFF AIR 'HEATER GAS' SWITCH"
7100 BEEP
7110 DISP "HIT CONTINUE TO PROCEED"
7120 PAUSE
7130 OUTPUT 709;"DO10,0"
7140 Pho=(Vpho-Vpho0)*Kpho+Pbar
7150 Volts=Vtho
7160 GOSUB Tcalc
7170 Tho=T
7180 Mho=Kkho*Ckho*Pho*.7854*(Dhochoke^2)/(Tho^.5)
7190 PRINT USING "Q"
7200 PRINT USING "4A,DD.DDDDD";"Mho=";Mho

```

```

5900 IF X$="Y" THEN GOTO Dtheffcalc
5910 Pnew=(PaxMaird/Mair)-Pbar
5920 PRINT "RESET Pa TO";Pnew;"Psiq"
5930 DISP "HIT CONTINUE AFTER RESET OF Pa"
5940 PAUSE
5950 GOTO Paset
5960 Dtheffcalc: ! CALCULATE EFFECTIVE THROAT DIAMETER, CHARACTERIS
TIC EXHAUST VELOCITY, THRUST BOTH THEORETICAL AND MEASURED
5970 Cstar=(Gc*Rair*Ti*((Gammaair+1)/2)^((Gammaair+1)/(Gammaair-1))/Gammaair)^
.5
5980 Cfair=.7396+.5293-(14.7/Pc)
5990 Dtheff=((Cstar*Mair)/(1.7854*Pc*Gc))^5)
6000 PRINT "Cstarair(BASED ON Ti)=";Cstar;"(ft/sec)"
6010 PRINT "Cfair=";Cfair
6020 PRINT "Dtheff=";Dtheff;"(in)"
6030 PRINT "Pco=";Pc;"Psiq"
6040 PRINT "Ti=";Ti;" R"
6050 F=(Vf-Vf0)*Kf
6060 Fair=Cfair*Pc*.7854*(Dtheff^2)
6070 PRINT "Fair(BASED ON Pc)=";Fair;"(Lbf)"
6080 PRINT "Fair(MEASURED)=";F;"(Lbf)"
6090 IF K0=0 THEN GOTO 6170
6100 INPUT "DO YOU WANT PRINTOUT OF POST RUN DATA?(Y/N)",Yy$
6110 IF Yy$="N" THEN GOTO Finish
6120 Headingprint: !
6130 PRINTER IS 701
6140 PRINT USING "6/"
6150 PRINT "***** POST RUN DATA COLD AIR, CHOKED *****"
6160 GOTO Preprint
6170 INPUT "DO YOU WANT PRINTOUT OF PRE-RUN DATA?(Y/N)",Xx$
6180 IF Xx$="Y" THEN GOTO Preprint
6190 GOTO Skipprint
6200 Preprint: !
6210 PRINTER IS 701
6220 IF K0=1 THEN GOTO 6240
6230 PRINT "**** PRE-RUN DATA, USING COLD AIR ONLY AND CHO
KED FLOW ****"
6240 PRINT ""
6250 PRINT USING "12A,2X,9A "; "TEST DATE IS",Date$
6260 PRINT "Cstarair(BASED ON Ti)=";Cstar;"(ft/sec)"
6270 PRINT "Cfair=";Cfair
6280 PRINT "Dtheff=";Dtheff;"(in)"
6290 PRINT "Pco=";Pc;"Psiq"
6300 PRINT "Ti=";Ti;" R"
6310 PRINT "Fair(BASED ON Pc)=";Fair;"(Lbf)"
6320 PRINT "Fair(MEASURED)=";F;"(Lbf)"
6330 PRINT "Mair=";Mair;"Lbm/sec"
6340 PRINTER IS 1
6350 IF K0=1 THEN GOTO Finish
6360 Skipprint: !
6370 DISP "HIT CONTINUE TO PROCEED TO NEXT FLOW RATE SET UP"
6380 PAUSE
6390 Paskip: !
6400 PRINT USING "0"
6410 INPUT "DO YOU WANT TO PRESET THE HEATER FUEL FLOW RATE? (Y/N)",Zz$
6420 IF Zz$="N" THEN GOTO Phfskip
6430 !*****
6440 PRINT "SET THE DESIRED VALUE OF Phf USING THE HAND LOADER/PRESSURE GAGE"
6450 !*****
6460 DISP "HIT CONTINUE WHEN READY"
6470 PAUSE
6480 Phfset: !
6490 PRINT USING "0"
6500 PRINT "MANUALLY TURN ON AIR 'HEATER GAS' SWITCH"
6510 DISP "HIT CONTINUE TO PROCEED"
6520 PAUSE
6530 OUTPUT 709;"AC3"
6540 OUTPUT 722;"T3"

```

```

5250 IF Zz$="Y" THEN GOTO Nochange
5260 Changevariable: !
5270 PRINT "INPUT VARIABLE NAME= CORRECTED VALUE"
5280 PRINT "A STRING VARIABLE MUST BE ENCLOSED IN QUOTATION MARKS"
5290 DISP "HIT EXECUTE AND THEN CONTINUE AFTER CORRECTION "
5300 PAUSE
5310 GOTO Change1
5320 Nochange: !
5330 !*****
5340 ! B. FLOW RATE SET-UPS
5350 !*****
5360 PRINT USING "B"
5370 INPUT "DO YOU WANT TO PRESET THE AIR FLOW RATE?(Y/N)",Zz$
5380 IF Zz$="N" THEN GOTO Paset
5390 PRINT "SET THE DESIRED VALUE OF Pa(psig) USING THE HAND LOADER /PRESSURE G
AGE"
5400 PRINT USING "3/"
5410 PRINT "THE HAND LOADER SHOULD BE 20 PSIG MORE THAN DESIRED PRESSURE"
5420 Paset: !
5430 PRINT USING "3/"
5440 PRINT "MANUALLY INITIATE AIR FLOW BY TURNING 'MAIN AIR' TO 'ON' AND PUSHI
NG 'PRI' ON CONTROL PANEL"
5450 DISP "HIT CONTINUE WHEN READY"
5460 PAUSE
5470 WAIT 3
5480 OUTPUT 709;"AC2"
5490 OUTPUT 722;"T3"
5500 ENTER 722;Vpa
5510 OUTPUT 709;"AC9"
5520 OUTPUT 722;"T3"
5530 ENTER 722;Vta
5540 OUTPUT 709;"AC0"
5550 OUTPUT 722;"T3"
5560 ENTER 722;Vpc
5570 OUTPUT 709;"AC8"
5580 OUTPUT 722;"T3"
5590 ENTER 722;Vti
5600 OUTPUT 709;"AC5"
5610 OUTPUT 722;"T3"
5620 ENTER 722;Vf
5630 CLEAR 709
5640 OUTPUT 709;"DC10,1" ! DIGITALLY CLOSE CIRCUIT 1
5650 WAIT 1
5660 OUTPUT 709;"DO10,1" ! DIGITALLY OPEN CIRCUIT 1
5670 KEEP
5680 PRINT "TURN OFF 'MAIN AIR'"
5690 DISP "HIT CONTINUE TO PROCEED"
5700 PAUSE
5710 Pa=(Vpa-Vpa0)*Kpa+Pbar
5720 Pc=(Vpc-Vpc0)*Kpc+Pbar
5730 Volts=Vta
5740 GOSUB Tcalc ! CONVERSION FROM VOLTAGE TO TEMPERATURE
5750 Ta=T
5760 Volts=Vti
5770 GOSUB Tcalc ! CONVERSION FROM VOLTAGE TO TEMPERATURE
5780 Ti=T
5790 Mair=Kmair*Cdair*Pa*.7854*(Dairchoke^2)/(Ta^.5)
5800 PRINT USING "B"
5810 PRINT USING "5A,2X,DDD.DDDDD*";"Mair=";Mair
5820 PRINT USING "14A,DDD.DDD*";"Mair DESIRED=";Maird
5830 Ratio=Mair/Maird
5840 PRINT USING "20A,D.DDD,2X,3A,1X,DDDD.DD,1A,3X,3A,DDDD.DD,1A*";"Mair/DESIRE
D Mair=";Ratio;"Ta=";Ta;"R","Ti=";Ti;"R"
5850 Pq=Pa-Pbar
5860 PRINT USING "4A,DDDD.DD,4A*";"Pa =" ;Pq;"Psig"
5870 PRINT USING "4A,DDDD.DD,1A*";"Ta =" ;Ta;"R"
5880 IF Ka=1 THEN GOTO Dtheffcalc ! DETERMINE PRE-RUN OR POST-RUN
5890 INPUT "IS AIR FLOW RATE ACCURATE ENOUGH? (Y/N)",Xx$

```

```

4680 INPUT "THE AIR CHOKE DISCHARGE COEFFICIENT",Cdair
4690 INPUT "THE AIR HEATER FUEL CHOKE DISCHARGE COEFFICIENT",Cdhf
4700 INPUT "THE AIR HEATER OXYGEN CHOKE DISCHARGE COEFFICIENT",Cdho
4710 INPUT "THE IGNITION GAS CHOKE DISCHARGE COEFFICIENT",Cdif
4720 INPUT "THE PURGE GAS CHOKE DISCHARGE COEFFICIENT",Cdp
4730 INPUT "THE AIR HEATER FUEL FLOW RATE CONSTANT,Kmhf",Kmhf
4740 INPUT "THE IGNITION GAS FLOW RATE CONSTANT,Kmif",Kmf
4750 INPUT "THE PURGE GAS FLOW RATE CONSTANT,Kmp",Kmp
4760 INPUT "GAMMA FOR HEATER FUEL,Gammahf",Gammahf
4770 INPUT "GAMMA FOR IGNITION FUEL,Gammaif",Gammaif
4780 INPUT "GAMMA FOR PURGE GAS,Gammap",Gammap
4790 INPUT "GAS CONSTANT FOR HEATER FUEL,Rhf(ft.lbf/lbm.R)",Rhf
4800 INPUT "GAS CONSTANT FOR IGNITION FUEL,Rif(ft.lbf/lbm.R)",Rif
4810 INPUT "GAS CONSTANT FOR PURGE GAS,Rp(ft.lbf/lbm.R)",Rp
4820 INPUT "THE AIR CHOKE DIAMETER,Dairchoke(in)",Dairchoke
4830 INPUT "THE HEATER FUEL CHOKE DIAMETER,Dhfuchoke(in)",Dhfuchoke
4840 INPUT "THE IGNITION OXYGEN CHOKE DIAMETER,Dhtoxchoke(in)",Dhtoxchoke
4850 INPUT "THE IGNITION FUEL CHOKE DIAMETER,Dignfuchoke(in)",Dignfuchoke
4860 INPUT "THE PURGE CHOKE DIAMETER,Dpurgechoke(in)",Dpurgechoke
4870 INPUT "THE DESIRED MASS FLOW RATE OF AIR,Maird(lbm/sec)",Maird
4880 INPUT "THE DESIRED MASS FLOW RATE OF heater FUEL,Mhfd(lbm/sec)",Mhfd
4890 INPUT "THE DESIRED MASS FLOW RATE OF heater OXYGEN,Mhod(lbm/sec)",Mhod
4900 INPUT "THE DESIRED MASS FLOW RATE OF IGNITION FUEL,Mifd(lbm/sec)",Mifd
4910 INPUT "THE DESIRED MASS FLOW RATE OF PURGE,Mpd(lbm/sec)",Mpd
4920 INPUT "THE INJECTION GAS,Injectgas",Injectgas
4930 !*****
4940 !* CHECK THE INPUT DATA *
4950 !*****
4960 Chancel: !
4970 PRINT USING "0"
4980 PRINT USING "14A,9A,5X,14A,9A,5X,14A,9A,2X,14A,DDDD.DDDD";"Testno=";Testno
$,"Date=";Date$,"Fuelid=";Fuelid$,"Pbar=";Pbar
4990 PRINT USING "14A,9A,5X,14A,9A,5X,14A,9A,5X,14A,9A";"Heaterfuel=";Heaterfuel$,"Ignitionfuel=";Ignitionfuel$,"Purge gas=";Purgegas$
5000 PRINT USING "14A,DDDD.DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Wtf1=";Wtf1,"Dc=";Dc,"Lo=";Lo
5010 PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Di=";Di,"Dth=";Dth
5020 PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD,2X,14A,DDDD.DDDD";"Tma=";Tma,"Tmi=";Tmi,"Tmb=";Tmb,"Tmn=";Tmn
5030 PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Dairchoke=";Dairchoke,"Dhtfuchoke=";Dhtfuchoke
5040 PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Dhtoxchoke=";Dhtoxchoke,"Dignfuchoke=";Dignfuchoke
5050 PRINT USING "14A,DDDD.DDDD";"Dpurgechoke=";Dpurgechoke
5060 PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Cdair=";Cdair,"Cdhf=";Cdhf,"Cdho=";Cdho
5070 PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Cdn=";Cdn,"Cdif=";Cdif
5080 PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Gammahf=";Gammahf,"Gammaif=";Gammaif
5090 PRINT USING "14A,DDDD.DDDD";"Gammap=";Gammap
5100 PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Rhf=";Rhf,"Rif=";Rif,"Rp=";Rp
5110 PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Kmhf=";Kmhf,"Kmf=";Kmf,"Kmp=";Kmp
5120 PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Kaho=";Kaho,"Kmaif=";Kmaif
5130 PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Maird=";Maird,"Tid=";Tid
5140 PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD,2X,14A,DDDD.DDDD";"Mhfd=";Mhfd,"Mhod=";Mhod,"Mifd=";Mifd,"Mpd=";Mpd
5150 PRINT "INJECTION GAS IS",Injectgas
5160 !*****
5170 !* VARIABLE CORRECTION
5180 !*****
5190 PRINT USING "4/"
5200 PRINT "CHECK ALL VALUES"
5210 DISP "HIT 'CONTINUE' TO PROCEED TO CORRECTION OR NEXT SUBROUTINE"
5220 PAUSE
5230 INPUT "VARIABLE OK? (Y/N)",Z1$
5240 IF Z1$="N" THEN GOTO Changevariable

```

```

4000 Kpp=Ppmax/(Vppmax-Vpp0)
4010 PRINT "Kpp=";Kpp
4020 BEEP
4030 INPUT "READING OK? (Y/N)",Zt$
4040 IF Zt$="N" THEN GOTO Ppmaxcal
4050 Fcal: !
4060 IF Ff=0. THEN GOTO Endcal
4070 !*****
4080 PRINT "**CALIBRATION OF F, THE THRUST STAND LOAD CELL**"
4090 !*****
4100 F0cal: !
4110 PRINT "****ZERO CALIBRATION****"
4120 PRINT "INSURE THAT THE 'ZERO' TARE WEIGHT IS ON THE TRAY"
4130 DISP "HIT CONTINUE WHEN READY"
4140 PAUSE
4150 REMOTE 709
4160 OUTPUT 709;"AC5"
4170 OUTPUT 722;"T3"
4180 ENTER 722;Vf0
4190 PRINT "Vf0=";Vf0
4200 INPUT "READING OK? (Y/N)",Zz$
4210 IF Zz$="N" THEN GOTO F0cal
4220 Fmaxcal: !
4230 PRINT USING "0"
4240 PRINT "****CALIBRATION****"
4250 PRINT "APPLY MAXIMUM WEIGHT TO THE TRAY"
4260 INPUT "ENTER THE MAXIMUM WEIGHT IN LBS",Fmax
4270 DISP "HIT CONTINUE WHEN READY"
4280 PAUSE
4290 REMOTE 709
4300 OUTPUT 709;"AC5"
4310 OUTPUT 722;"T3"
4320 ENTER 722;Vfmax
4330 PRINT "Vfmax=";Vfmax,"Fmax=";Fmax
4340 Kf=Fmax/(Vfmax-Vf0)
4350 PRINT "Kf=";Kf
4360 BEEP
4370 INPUT "READING OK? (Y/N)",Zt$
4380 IF Zt$="N" THEN GOTO Fmaxcal
4390 Endcal: !
4400 PRINT "THIS ENDS THE CALIBRATIONS "
4410 !*****
4420 ! (3) PRE-RUN INPUTS, FLOW RATE SET-UP
4430 !*****
4440 ! A. PRE-RUN INPUTS
4450 !*****
4460 Inputvariables: !
4470 INPUT "DO YOU WANT TO INPUT NEW VARIABLES (Y/N)",Yy$
4480 IF Yy$="N" THEN GOTO Nochange
4490 PRINT "INPUT THE FOLLOWING TEST VARIABLES"
4500 PRINT "STRING VARIABLES MUST BE ENCLOSED IN QUOTATION MARKS"
4510 INPUT "THE TEST IDENTIFICATION NUMBER, A STRING VARIABLE",Testno$
4520 INPUT "TODAY'S DATE AS MO.DAY.YEAR, A STRING VARIABLE",Date$
4530 INPUT "THE BAROMETRIC PRESSURE",Pbar
4540 INPUT "THE FUEL IDENTIFICATION, A STRING VARIABLE",Fuelid$
4550 INPUT "THE AIR HEATER FUEL TYPE, A STRING VARIABLE",Heaterfuel$
4560 INPUT "THE SFRJ IGNITION FUEL TYPE, A STRING VARIABLE",Ignitionfuel$
4570 INPUT "THE PURGE GAS TYPE, A STRING VARIABLE",Purgegas$
4580 INPUT "THE INITIAL FUEL GRAIN WEIGHT (LRM)",Wfi
4590 INPUT "THE INITIAL FUEL GRAIN INTERNAL DIAMETER (IN)",Dp
4600 INPUT "THE INITIAL FUEL GRAIN LENGTH (IN)",Lp
4610 INPUT "THE AIR INLET DIAMETER (IN)",Di
4620 INPUT "THE MOTOR THROAT DIAMETER (IN)",Dth
4630 INPUT "THE DESIRED AIR INLET TEMPERATURE (R)",Tid
4640 INPUT "THE DESIRED IGNITION DELAY TIME (SEC)",Tma
4650 INPUT "THE DESIRED IGNITION TIME (SEC)",Tmi
4660 INPUT "THE DESIRED BURN TIME (SEC)",Tmb
4670 INPUT "THE DESIRED PURGE TIME (SEC)",Tmo

```

```

3320 ENTER 722;Vphomax
3330 PRINT "Vphomax=";Vphomax,"Phomax=";Phomax
3340 Kpho=Phomax/(Vphomax-Vpho0)
3350 PRINT "Kpho=";Kpho
3360 BEEP
3370 INPUT "READING OK? (Y/N)",Zz$
3380 IF Zz$="N" THEN GOTO Phomaxcal
3390 Pifcal: !
3400 !*****
3410 PRINT "**CALIBRATION OF Pif, THE SFRJ IGNITION FUEL PRESSURE TRANSDUCER**"
3420 !*****
3430 Pifocal: !
3440 PRINT "****ZERO CALIBRATION****"
3450 PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
3460 DISP "HIT CONTINUE WHEN READY"
3470 PAUSE
3480 REMOTE 709
3490 OUTPUT 709;"AC6"
3500 OUTPUT 722;"T3"
3510 ENTER 722;Upif0
3520 PRINT "Upif0=";Upif0
3530 INPUT "READING OK? (Y/N)",Zz$
3540 IF Zz$="N" THEN GOTO Pifocal
3550 Pifmaxcal: !
3560 PRINT USING "0"
3570 PRINT "****CALIBRATION****"
3580 PRINT "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
3590 INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Pifmax
3600 DISP "HIT CONTINUE WHEN READY"
3610 PAUSE
3620 REMOTE 709
3630 OUTPUT 709;"AC6"
3640 OUTPUT 722;"T3"
3650 ENTER 722;Upifmax
3660 PRINT "Upifmax=";Upifmax,"Pifmax=";Pifmax
3670 Kpif=Pifmax/(Upifmax-Upif0)
3680 PRINT "Kpif=";Kpif
3690 BEEP
3700 INPUT "READING OK? (Y/N)",Zz$
3710 IF Zz$="N" THEN GOTO Pifmaxcal
3720 Ppcal: !
3730 !*****
3740 PRINT "**CALIBRATION OF Pp, THE SFRJ PURGE GAS PRESSURE TRANSDUCER**"
3750 !*****
3760 Ppocal: !
3770 PRINT "****ZERO CALIBRATION****"
3780 PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
3790 DISP "HIT CONTINUE WHEN READY"
3800 PAUSE
3810 REMOTE 709
3820 OUTPUT 709;"AC7"
3830 OUTPUT 722;"T3"
3840 ENTER 722;Upp0
3850 PRINT "Upp0=";Upp0
3860 INPUT "READING OK? (Y/N)",Zz$
3870 IF Zz$="N" THEN GOTO Ppocal
3880 Ppmaxcal: !
3890 PRINT USING "0"
3900 PRINT "****CALIBRATION****"
3910 PRINT "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
3920 INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Ppmax
3930 DISP "HIT CONTINUE WHEN READY"
3940 PAUSE
3950 REMOTE 709
3960 OUTPUT 709;"AC7"
3970 OUTPUT 722;"T3"
3980 ENTER 722;Uppmax
3990 PRINT "Uppmax=";Uppmax,"Ppmax=";Ppmax

```



```

2640 WAIT 2
2650 OUTPUT 722;"T3"
2660 ENTER 722;Vphmax
2670 PRINT "Vphmax=";Vphmax;"Phmax=";Phmax
2680 Kph=Phmax/(Vphmax-Vph0)
2690 PRINT "Kph=";Kph
2700 BEEP
2710 INPUT "READING OK? (Y/N)",Zz$
2720 IF Zz$="N" THEN GOTO Phmaxcal
2730 Phfcal: !
2740 !*****
2750 PRINT "**CALIBRATION OF Phf, THE AIR HEATER FUEL PRESSURE TRANSDUCER**"
2760 !*****
2770 Phf0cal: !
2780 PRINT "****ZERO CALIBRATION****"
2790 PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
2800 DISP "HIT CONTINUE WHEN READY"
2810 PAUSE
2820 REMOTE 709
2830 OUTPUT 709;"AC3"
2840 OUTPUT 722;"T3"
2850 ENTER 722;Vphf0
2860 PRINT "Vphf0=";Vphf0
2870 INPUT "READING OK? (Y/N)",Zz$
2880 IF Zz$="N" THEN GOTO Phf0cal
2890 Phfmaxcal: !
2900 PRINT USING "E"
2910 PRINT "****CALIBRATION****"
2920 PRINT "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
2930 INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Phfmax
2940 DISP "HIT CONTINUE WHEN READY"
2950 PAUSE
2960 REMOTE 709
2970 OUTPUT 709;"AC3"
2980 OUTPUT 722;"T3"
2990 ENTER 722;Vphfmax
3000 PRINT "Vphfmax=";Vphfmax;"Phfmax=";Phfmax
3010 Kphf=Phfmax/(Vphfmax-Vphf0)
3020 PRINT "Kphf=";Kphf
3030 BEEP
3040 INPUT "READING OK? (Y/N)",Zz$
3050 IF Zz$="N" THEN GOTO Phfmaxcal
3060 Ph0cal: !
3070 !*****
3080 PRINT "**CALIBRATION OF Ph0, THE AIR HEATER OXYGEN PRESSURE TRANSDUCER**"
3090 !*****
3100 Ph00cal: !
3110 PRINT "****ZERO CALIBRATION****"
3120 PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
3130 DISP "HIT CONTINUE WHEN READY"
3140 PAUSE
3150 REMOTE 709
3160 OUTPUT 709;"AC4"
3170 OUTPUT 722;"T3"
3180 ENTER 722;Vph00
3190 PRINT "Vph00=";Vph00
3200 INPUT "READING OK? (Y/N)",Zz$
3210 IF Zz$="N" THEN GOTO Ph00cal
3220 Ph0maxcal: !
3230 PRINT USING "E"
3240 PRINT "****CALIBRATION****"
3250 PRINT "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
3260 INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Ph0max
3270 DISP "HIT CONTINUE WHEN READY"
3280 PAUSE
3290 REMOTE 709
3300 OUTPUT 709;"AC4"
3310 OUTPUT 722;"T3"

```

```

1960 Kpa=(Pamax)/(Upamax-Upa0)
1970 PRINT "Kpa= ";Kpa
1980 BEEP
1990 INPUT "READING OK? (Y/N)",Zz$
2000 IF Zz$="N" THEN GOTO Pamacal
2010 Pccal: !
2020 !*****
2030 PRINT "**CALIBRATION OF Pc, THE SFRJ MOTOR CHAMBER PRESSURE TRANSDUCER**"
2040 !*****
2050 Pc0cal: !
2060 PRINT "**** ZERO PRESSURE ****"
2070 PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
2080 DISP "HIT CONTINUE WHEN READY"
2090 PAUSE
2100 REMOTE 709
2110 OUTPUT 709;"AC0"
2120 WAIT 2
2130 OUTPUT 722;"T3"
2140 ENTER 722;Vpc0
2150 PRINT "Vpc0=";Vpc0
2160 BEEP
2170 INPUT "READING OK? (Y/N)",Zz$
2180 IF Zz$="N" THEN GOTO Pc0cal
2190 Pcmacal: !
2200 PRINT USING "@ "
2210 PRINT "**** CALIBRATION ****"
2220 PRINT "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
2230 INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Pcmax
2240 DISP "HIT CONTINUE WHEN READY"
2250 PAUSE
2260 REMOTE 709
2270 OUTPUT 709;"AC0"
2280 WAIT 2
2290 OUTPUT 722;"T3"
2300 ENTER 722;Vpcmax
2310 PRINT "Vpcmax=";Vpcmax,"Pcmax=";Pcmax
2320 Kpc=Pcmax/(Vpcmax-Vpc0)
2330 PRINT "Kpc=";Kpc
2340 BEEP
2350 INPUT "READING OK? (Y/N)",Zz$
2360 IF Zz$="N" THEN GOTO Pcmacal
2370 Phcal: !
2380 !*****
2390 PRINT "**CALIBRATION OF Ph, THE SFRJ MOTOR HEAD-END PRESSURE TRANSDUCER**"
2400 !*****
2410 Ph0cal: !
2420 PRINT "****ZERO PRESSURE****"
2430 PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
2440 DISP "HIT CONTINUE WHEN READY"
2450 PAUSE
2460 REMOTE 709
2470 OUTPUT 709;"AC1"
2480 WAIT 2
2490 OUTPUT 722;"T3"
2500 ENTER 722;Vph0
2510 PRINT "Vph0=";Vph0
2520 BEEP
2530 INPUT "READING OK? (Y/N)",Zz$
2540 IF Zz$="N" THEN GOTO Ph0cal
2550 Phmacal: !
2560 PRINT USING "@ "
2570 PRINT "****CALIBRATION****"
2580 DISP "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
2590 INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Phmax
2600 DISP "HIT CONTINUE WHEN READY"
2610 PAUSE
2620 REMOTE 709
2630 OUTPUT 709;"AC1"

```

```

1350 IF Volts=.01509 AND Volts<.00831 THEN T=((Volts-.00609)/.000022
21+7+1
1360 IF Volts=.00831 AND Volts<.01056 THEN T=((Volts-.00831)/.000022
51+8+0
1370 IF Volts=.01056 AND Volts<.01285 THEN T=((Volts-.01056)/.000022
91+9+0
1380 IF Volts=.01285 AND Volts<.01518 THEN T=((Volts-.01285)/.000023
31+10+0
1390 IF Volts=.01518 AND Volts<.01752 THEN T=((Volts-.01518)/.000023
41+11+0
1400 IF Volts=.01752 AND Volts<.01988 THEN T=((Volts-.01752)/.000023
61+12+0
1410 IF Volts=.01988 AND Volts<.02225 THEN T=((Volts-.01988)/.000023
71+13+0
1420 IF Volts>.02225 THEN GOTO TooHigh
1430 RETURN
1440 TooHigh:
1450 PRINT "TEMPERATURE SET AT 1460 R"
1460 PRINT "I=",I
1470 T=1460
1480 BEEP 500,.1
1490 WAIT 1
1500 BEEP 500,.1
1510 RETURN
1520 Paocal:
1530 *****
1540 (2) TRANSDUCER CALIBRATIONS
1550 *****
1560 THERE ARE 6 PRESSURE TRANSDUCERS AND ONE LOAD CELL FOR THRUST WHICH
1570 MUST BE CALIBRATED. TRANSDUCER LINEARITY MUST BE VERIFIED BEFORE THIS
1580 CALIBRATION PROCEDURE IS EMPLOYED. THE ORDER OF CALIBRATION IS AS
1590 FOLLOWS: Pa, Pc, Ph, Phf, Pho, Pif, Po, F
1600 THE FOLLOWING TWO LINES SET UP 722 AND 709 FOR DATA ACQUISITION"
1610 CLEAR 709 ! CLEAR 3497A DATA ACQUISITION/CONTROL UNIT
1620 CLEAR 722 ! CLEAR 3456A DIGITAL VOLTMETER
1630 REMOTE 709 ! MAKE 3497A UNIT TO REMOTE MODE
1640 OUTPUT 722;"LIR31STNZ110ST1T4QX1" ! 10 READING PER TRIGGER AND STORE
1650 Paocal:
1660 *****
1670 PRINT "** CALIBRATION OF Pa, THE AIR SONIC CHOKE PRESSURE TRANSDUCER"
1680 *****
1690 Paocal:
1700 PRINT "***** Z E R O P R E S S U R E *****"
1710 PRINT "INSURE THAT NO PPESSURE IS APPLIED TO THE TRANSDUCER"
1720 DISP "HIT CONTINUE WHEN READY TO TAKE ZERO READING"
1730 PAUSE
1740 REMOTE 709
1750 OUTPUT 709;"AC2" ! ACQUIRE CHANNEL 2
1760 WAIT 2
1770 OUTPUT 722;"T3" ! INITATE SINGLE TRIGGER
1780 ENTER 722;Uoa0 ! READ VOLTAGE
1790 PRINT "Uoa0=";Uoa0
1800 BEEP
1810 INPUT "READING OK? (Y/N)",Zz$
1820 IF Zz$="N" THEN GOTO Paocal
1830 Pamaxcal:
1840 PRINT USING "0" ! CLEAR SCREEN
1850 PRINT "***** C A L I B R A T I O N *****"
1860 PRINT "APPLY MAXIMUM PRESSURE USING THE DEAD-WEIGHT TESTER"
1870 INPUT "ENTER THE MAXIMUM PRESSURE IN psiq",Pamax
1880 DISP "HIT CONTINUE WHEN READY"
1890 PAUSE
1900 REMOTE 709
1910 OUTPUT 709;"AC2"
1920 WAIT 2
1930 OUTPUT 722;"T3"
1940 ENTER 722;Upamax
1950 PRINT "Upamax=";Upamax,"Pamax=";Pamax

```

```

690 Tma TIME BETWEEN SFRJ AIR FLOW AND IGNITION, sec
700 Tmb BURN TIME AFTER Tm1, sec
710 Tm1 IGNITION DURATION AFTER Tma, sec
720 Tmp PURGE DURATION AFTER Tmb, sec
730 Tp TEMPERATURE, PURGE GAS SONIC CHOKE, R
740 Wtfi INITIAL FUEL GRAIN WEIGHT, Lbm
750
760
770 REEP 1000,.1
780 PRINT USING "0"
790 PRINT USING "6/"
800 PRINT " 1.2 Volts MAXIMUM into Acquisition System!!!"
810 THE RECORDED VARIABLES (VOLTAGES) AND LOCATIONS ARE:
820 (NOTE: THE MAXIMUM ALLOWABLE VOLTAGE INTO THE SYSTEM IS 1.2 VOLTS)
830
840 VARIABLE 3497 DACU SCANNER NUMBER 0
850
860 Pa 2
870 Pc 0
880 Ph 1
890 Phf 3
900 Pho 4
910 Pif 6
920 Pp 7
930 F 5
940 Ta 9
950 Thf 10
960 Tho 11
970 Ti 8
980 Tif 12
990 Tp 13
1000
1010
1020 ALL FLOW RATES ARE CALCULATED USING THE ONE-DIMENSIONAL, ISENTROPIC
1030 FLOW EXPRESSIONS WITH FIXED PROPERTIES. SMALL SONIC NOZZLES HAVE
1040 MEASURED DISCHARGE COEFFICIENTS. THE AIR FLOW NOZZLE USES AN ASSUMED
1050 DISCHARGE COEFFICIENT (Cd) OF 0.97.
1060
1070  $M (LBM/SEC) = Cd * P * A * Km / T^{.5}$ 
1080
1090 Km IS THE GAS-DEPENDENT SONIC CHOKE FLOW RATE CONSTANT
1100
1110  $Km = SQRT((Gamma * Gc / R) * (2 / (Gamma + 1))^{((Gamma + 1) / (Gamma - 1))})$ 
1120
1130 APPROPRIATE CONSTANTS ARE:
1140
1150 GAS MOLECULAR WT. GAS CONST. CP GAMMA Km
1160
1170 AIR 29.0 53.3 .240 1.40 .5320
1180 O2 32.0 48.3 .217 1.40 .5589
1190 CH4 16.03 96.4 .593 1.32 .3876
1200 C2H4 28.03 55.1 .400 1.22 .4985
1210 ARGON 39.9 38.7 .124 1.67 .6626
1220
1230 ALL THERMOCOUPLES USED ARE CHROMEL vs ALUMEL (TYPE K) WITH
1240 ELECTRONIC ICE POINTS. TEMPERATURE READINGS (VOLTAGES) ARE
1250 CONVERTED TO DEGREES RANKINE (R) PER "INDUSTRIAL INSTRUMENTATION" BY
1260 D.D.P. ECKMAN (PAGE 369). THIS CALCULATION IS PERFORMED IN SUBROUTINE
1270 Tcalc. TEN VOLTAGE INTERVALS ARE USED BETWEEN 460 AND 1460 R.
1280 Gc=32.174
1290 Ko=0 ! POST RUN CONTROL FLAG
1300 GOTO Transcal
1310 Tcalc:
1320 IF Volts<.00153 THEN T=((Volts+.00068)/.0000220)+460
1330 IF Volts>=.00153 AND Volts<.00382 THEN T=((Volts-.00153)/.000023
0)+560
1340 IF Volts>=.00382 AND Volts<.00609 THEN T=((Volts-.00382)/.000022
7)+660

```

APPENDIX A

COMPUTER PROGRAM FOR EXPERIMENT CONTROL AND DATA REDUCTION

```

10  ISFRJTEST
20  SOLID FUEL RAMJET DATA ACQUISITION AND DATA REDUCTION PROGRAM,
30  THIS PROGRAM IS DIVIDED INTO FIVE PARTS:
40      (1) VARIABLE DEFINITIONS AND NOMENCLATURE
50      (2) TRANSDUCER CALIBRATIONS
60      (3) PRE-RUN INPUTS, FLOW SET-UPS
70      (4) THE TEST SEQUENCE AND DATA COLLECTION
80      (5) POST-RUN OPERATIONS
90  *****
100 (1) VARIABLE DEFINITIONS AND NOMENCLATURE
110 *****
120      SYMBOL      DEFINITION
130      A          ANALOG CHANNEL NUMBER
140      Cdaair      DISCHARGE COEFFICIENT, AIR SONIC CHOKE
150      Cdhf        DISCHARGE COEFFICIENT, HEATER FUEL SONIC CHOKE
160      Cdhho       DISCHARGE COEFFICIENT, OXYGEN MAKE-UP SONIC CHOKE
170      Cdif        DISCHARGE COEFFICIENT, IGNITION FUEL SONIC CHOKE
180      Cdp         DISCHARGE COEFFICIENT, PURGE GAS SONIC CHOKE
190      Cf          THRUST COEFFICIENT
200      Cstarth     THEORETICAL C*, FT/SEC
210      Cstarair    C* FOR AIR FLOW BASED ON Dtheff
220      Dairchoke   AIR SONIC CHOKE DIAMETER
230      Date$       Test Date  Mo-Day-Yr
240      Dhfchoke    AIR HEATER FUEL SONIC CHOKE DIAMETER
250      Dhochoke    OXYGEN MAKE-UP SONIC CHOKE DIAMETER
260      Di          MOTOR INLET DIAMETER, IN.
270      Difchoke    IGNITION FUEL SONIC CHOKE DIAMETER
280      Dp          MOTOR FUEL PORT DIAMETER, IN.
290      Dpchoke     PURGE GAS SONIC CHOKE DIAMETER
300      Dth         MOTOR EXHAUST NOZZLE THROAT DIAMETER, IN.
310      Dtheff      EFFECTIVE THROAT DIAMETER, IN.
320      F           THRUST
330      Fuelid$     FUEL IDENTIFICATION
340      Gc          GRAVITATIONAL CONSTANT (32.174)
350      Heaterfuel$ FUEL IDENTIFICATION
360      Ignitionfuel$ SFRJ IGNITION FUEL I.D
370      Kmair       AIR SONIC CHOKE FLOW RATE CONSTANT
380      Kmhf        HEATER FUEL SONIC CHOKE FLOW RATE CONSTANT
390      Kmho        OXYGEN MAKE-UP SONIC CHOKE FLOW RATE CONSTANT
400      Kmif        IGNITION FUEL SONIC CHOKE FLOW RATE CONSTANT
410      Kmo         PURGE GAS SONIC CHOKE FLOW RATE CONSTANT
420      Lp         FUEL GRAIN LENGTH, IN.
430      Mair        AIR FLOW RATE, Lbm/SEC
440      Maird       DESIRED AIR FLOW RATE, Lbm/sec
450      Mhf         HEATER FUEL FLOW RATE, Lbm/sec
460      Mhfd        DESIRED HEATER FUEL FLOW RATE Lbm/sec
470      Mho         HEATER OXYGEN FLOW RATE, Lbm/sec
480      Mhod        DESIRED HEATER OXYGEN FLOW RATE, Lbm/sec
490      Mif         IGNITION FUEL FLOW RATE, Lbm/sec
500      Mifd        DESIRED IGNITION FUEL FLOW RATE, Lbm/sec
510      Mp          PURGE GAS FLOW RATE, Lbm/sec
520      Mpd         DESIRED PURGE GAS FLOW RATE, Lbm/sec
530      Pa          PRESSURE, AIR SONIC CHOKE, Psia
540      Pbar        BAROMETRIC PRESSURE, Psia
550      Pc          PRESSURE, CHAMBER, Psia
560      Ph          PRESSURE, MOTOR HEAD-END, Psia
570      Phf         PRESSURE, HEATER FUEL SONIC CHOKE, Psia
580      Pho         PRESSURE, HEATER OXYGEN SONIC CHOKE, Psia
590      Pif         PRESSURE, IGNITION FUEL SONIC CHOKE, Psia
600      Pp          PRESSURE, PURGE GAS SONIC CHOKE, Psia
610      Purdegas$   PURGE GAS I.D
620      Ta          TEMPERATURE, AIR SONIC CHOKE, R
630      Testno$     TEST I.D NO.
640      Thf         TEMPERATURE, HEATER FUEL SONIC CHOKE, R
650      Tho         TEMPERATURE, OXYGEN MAKE-UP SONIC CHOKE, R
660      Ti          TEMPERATURE, MOTOR AIR INLET, R
670      Tid         TEMPERATURE, DESIRED MOTOR AIR INLET, R
680      Tif         TEMPERATURE, IGNITION FUEL SONIC CHOKE, R

```

VI. CONCLUSIONS AND RECOMMENDATIONS

Additional tests using fuel-wall and step face injection of oxygen, gaseous fuel and/or heated air should be conducted to verify the initial results found in this investigation. However, the initial data from this investigation indicates that gaseous injection is not a viable technique for fuel regression rate control.

Fuel regression rate was found to be quite sensitive to small amounts of inlet air swirl without large changes in combustion efficiency. Additional testing is recommended.

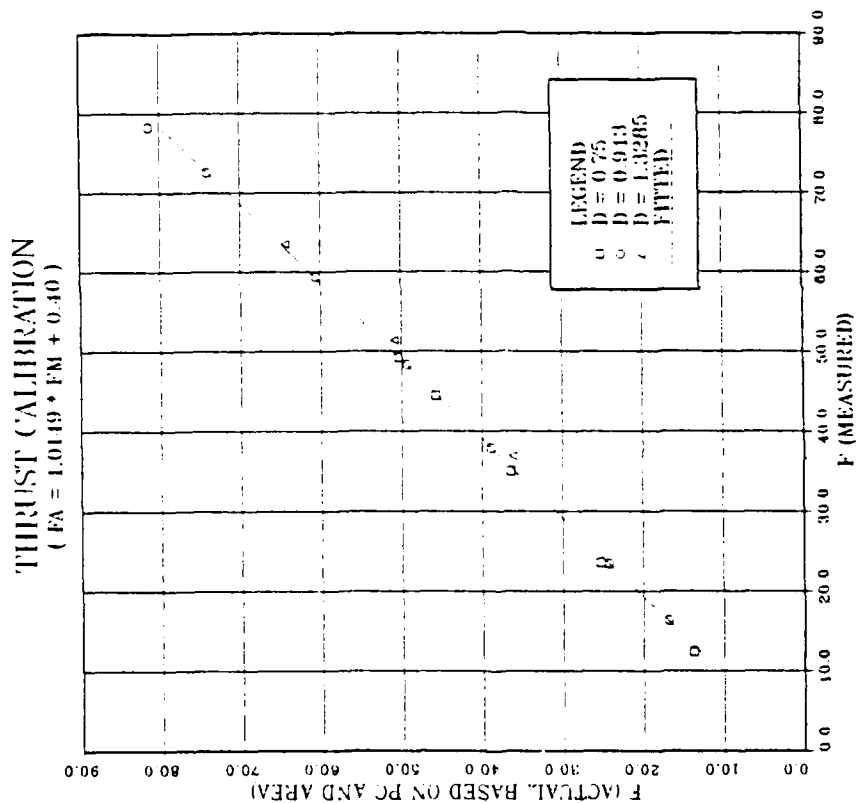


Figure 5.1.1 Thrust Calibration Curve, Measured vs Actual.

Table 3
Summary of Experimental Data (cont'd.)

Test number	27	28	29	30	31	32
ϕ	0.69	0.70	0.82	0.81	0.79	1.374
Pc (psia)	55.4	59.1	57.7	55.9	55.8	101.8
PEPCODE results						
Tth (°R)	3398	3917	3737	3724	3662	4283
γ	1.265	1.254	1.256	1.256	1.258	1.257
R (ft Lbf/Lbm°R)	56.18	55.93	54.93	53.27	55.68	56.82
Efficiency (based on Pc, analog)	83.4	81.5*	78.9	100	85.5	82.7 (78.7)**

* based on Pc, digital

** based on F, analog


```

7210 PRINT USING "11A,DD.DDDDD";Mairinject=";Mho
7220 PRINT USING "18A,DD.DDDDD";Mho DESIRED=";Mnod
7230 Ratio=Mho/Mnod
7240 PRINT USING "30A, DDDD.DDDD,3X,4A,DDDD.DD,1A";Mho/Mho DESIRED=";Rat
10,"Tho=";Tho,"R"
7250 Pg=Pho-Pbar
7260 PRINT USING "5A,DDDD.DD,1X,5A,5X,4A,DDDD.DD,1X,2A";Pho=";Pg;"Psig"
;"Tho=";Tho;"R"
7270 INPUT "IS THE HEATER OXYGEN FLOW RATE ENOUGH? (Y/N)?",Xx$
7280 IF Xx$="Y" THEN GOTO Phofin
7290 Phonew=(Pho*Mnod/Mho)-Pbar
7300 PRINT USING "14A,DDDD.DD,1X,4A";"RESET Pho TO ";Phonew;"Psig"
7310 DISP "HIT CONTINUE AFTER RESET OF Pho"
7320 PAUSE
7330 GOTO Phoset
7340 Phofin:
7350 DISP "HIT CONTINUE TO PROCEED TO NEXT FLOW RATE SET UP"
7360 PAUSE
7370 Phoskip:
7380 PRINT USING "@@"
7390 INPUT "DO YOU WANT TO PRESET THE IGNITION FUEL FLOW RATE?(Y/N)",Zz$
7400 IF Zz$="N" THEN GOTO Pifskip
7410 !*****
7420 PRINT " SET THE DESIRED VALUE OF Pif USING THE HAND LOADER/PRESSURE GAGE"
7430 !*****
7440 DISP "HIT CONTINUE WHEN READY"
7450 PAUSE
7460 Pifset:
7470 PRINT "MANUALLY TURN ON 'IGN. GAS' SWITCH"
7480 DISP "HIT CONTINUE WHEN READY"
7490 PAUSE
7500 OUTPUT 709;"AC6"
7510 WAIT 1
7520 OUTPUT 722;"T3"
7530 ENTER 722;Upif
7540 OUTPUT 709;"AC12"
7550 OUTPUT 722;"T3"
7560 ENTER 722;Utif
7570 BEEP
7580 PRINT "MANUALLY TURN OFF 'IGN GAS' SWITCH"
7590 DISP "HIT CONTINUE TO PROCEED"
7600 PAUSE
7610 Pif=(Upif-Upif0)*Kpif+Pbar
7620 Volts=Utif
7630 GOSUB Tcalc
7640 Tif=T
7650 Mif=Kmif*Cdif*Pif*.7854*(Difchoke^2)/(Tif^.5)
7660 PRINT USING "@@"
7670 PRINT USING "4A,DD.DDDDD";Mif=";Mif
7680 PRINT USING "15A,DD.DDDDD";Mif DESIRED=";Mifd
7690 Ratio=Mif/Mifd
7700 PRINT USING "17A,D.DDD,3X,4A,DDDD.DDD,1A";Mif/Mif DESIRED=";Ratio,"Tif="
;"Tif","R"
7710 Pg=Pif-Pbar
7720 PRINT USING "4A,DDDD.DD,1X,4A,5X,4A,DDDD.DD,1X,1A";Pif=";Pg;"Psig";"Tif="
;"Tif";"R"
7730 INPUT "IS THE SFRJ IGNITION FUEL FLOW RATE ACCURATE ENOUGH? (Y/N)?",Xx$
7740 IF Xx$="Y" THEN GOTO Piffin
7750 Pifnew=(Pif*Mifd/Mif)-Pbar
7760 PRINT USING "12A,DDDD.DD,1X,4A";"RESET Pif TO";Pifnew;"Psig"
7770 DISP "HIT CONTINUE AFTER RESET OF Pif"
7780 PAUSE
7790 GOTO Pifset
7800 Piffin:
7810 DISP "HIT CONTINUE TO PROCEED TO NEXT FLOW RATE SET UP"
7820 PAUSE
7830 Pifskip:
7840 PRINT USING "@@"

```

```

7850 INPUT "DO YOU WANT TO PRESET THE PURGE FLOW RATE? (Y/N)",Zz$
7860 IF Zz$="N" THEN GOTO Ppskip
7870 !*****
7880 PRINT "SET THE DESIRED VALUE OF Pp USING THE HANDLOADER/PRESSURE GAGE"
7890 !*****
7900 DISP "HIT CONTINUE WHEN READY"
7910 PAUSE
7920 Ppset: !
7930 CLEAR 709
7940 OUTPUT 709;"DC10,1"
7950 WAIT 2
7960 OUTPUT 709;"AC7"
7970 OUTPUT 722;"T3"
7980 ENTER 722;Vpp
7990 OUTPUT 709;"AC13"
8000 OUTPUT 722;"T3"
8010 ENTER 722;Vtp
8020 OUTPUT 769;"DC10,1"
8030 Pp=(Vpp-Vpp0)*Kpp+Pbar
8040 Volts=Vtp
8050 GOSUB Tcalc
8060 Tp=T
8070 Mp=Kmp*Cdp*Pp*.7854*(Dpchoke^2)/(Tp^.5)
8080 PRINT USING "e"
8090 PRINT USING "3A,DD.DDDDD";"Mp=";Mp
8100 PRINT USING "13A,DD.DDDDD";"Mp DESIRED=";Mpd
8110 Ratio=Mp/Mpd
8120 PRINT USING "16A,D.DD,3X,3A,DDDD.DD,1A";"Mp/Mp DESIRED =" ;Ratio,"Tp=" Tp
      ,R"
8130 BEEP
8140 Pg=Pp-Pbar
8150 PRINT USING "3A,DDDD.DD,1X,4A,3X,4A,DDDD.DD,1X,1A";"Pp=";Pg;"Psig","Tp="
      ;Tp;"R"
8160 INPUT "IS THE PURGE GAS FLOW RATE ACCURATE ENOUGH? (Y/N)",Xx$
8170 IF Xx$="Y" THEN GOTO Ppfin
8180 Ppnew=(Pp*Mpd/Mp)-Pbar
8190 PRINT USING "16A,DDDD.DD,1X,4A";"RESET Pp TO";Ppnew;"Psig"
8200 DISP "HIT CONTINUE AFTER RESET OF Pp"
8210 PAUSE
8220 GOTO Ppset
8230 Ppfin: !
8240 Ppskip: !
8250 PRINT "THIS COMPLETES PRE-RUN SET-UP"
8260 !*****
8270 ! (4) THIS PORTION OF THE PROGRAM RUNS THE TEST AND COLLECTS THE DATA
8280 !*****
8290 !
8300 PRINT USING "e"
8310 DISP "SET TIMEDATE BY PRESSING K19 AND UPDATE, THEN EXECUTE, THEN HIT CON
      TINUE"
8320 BEEP
8330 PAUSE
8340 CLEAR 709
8350 CLEAR 722
8360 ! THE FOLLOWING PROGRAMS THE 3456A DVM
8370 OUTPUT 722;"L1Z0D0F10STD0FL0R3.10ST11STNS01TAQX1"
8380 PRINT "THE DESIRED RUN TIMES AND DELAYS NOW BE INPUT"
8390 INPUT "ENTER Tma,Tmi,Tmb,Tmp SEPARATED BY COMMA, THEN HIT CONTINUE",Tma,Tmi
      ,Tmb,Tmp
8400 Tshut=Tma+Tmi+Tmb+Tmp+1 ! ONE MORE SECOND FOR TAIL PART READING
8410 T4=Tma+Tmi
8420 T5=T4+Tmb
8430 T6=T5+Tmp
8440 OPTION BASE 1
8450 DIM In(500,14) ! STORAGE DEFINITION
8460 J=1
8470 A=1 ! CONTROL FLAGS
8480 A1=0

```

```

8490 A2=0
8500 A3=0
8510 A4=0
8520 V14=0
8530 PRINT USING "@ "
8540 DISP "TO INITIATE RUN, PUSH 'PRI-AIR SWITCH' "
8550 Monitor: ! WAIT UNTIL INITIATE
8560 OUTPUT 709;"AC14"
8570 OUTPUT 722;"T3"
8580 ENTER 722;V14
8590 IF V14=.5 THEN GOTO Startrun ! IF INITIATE RUN, IT WILL GIVE
0.8 VOLTS
8600 GOTO Monitor
8610 Startrun: !
8620 T0=TIMEDATE
8630 ON CYCLE .5 GOSUB Data
8640 ON DELAY Tshut GOTO Shutdown
8650 Timewait: ! WAIT 0.5 SECOND
8660 A=A+1
8670 GOTO Timewait
8680 Data: ! READ ALL DATA EVERY 0.5 SECONDS
8690 OUTPUT 709;"AC0AF0AL13"
8700 FOR I=1 TO 14
8710 OUTPUT 722;"T3"
8720 ENTER 722 USING "#,K";In(J,I)
8730 OUTPUT 709;"AS"
8740 NEXT I
8750 J=J+1
8760 T1=TIMEDATE
8770 IF A1=1 THEN GOTO Tmabypass
8780 IF DROUND(T1-T0,3))=Tma THEN
8790 OUTPUT 709;"DC10,2"
8800 OUTPUT 709;"DC10,3"
8810 A1=1
8820 END IF
8830 Tmabypass: !
8840 T1=TIMEDATE
8850 IF A2=1 THEN GOTO T4bypass
8860 IF DROUND(T1-T0,3))=T4 THEN
8870 OUTPUT 709;"DO10,2"
8880 OUTPUT 709;"DO10,3"
8890 A2=1
8900 END IF
8910 T4bypass: !
8920 T1=TIMEDATE
8930 IF A3=1 THEN GOTO T5bypass
8940 IF DROUND(T1-T0,3))=T5 THEN
8950 OUTPUT 709;"DC10,1"
8960 A3=1
8970 END IF
8980 T5bypass: !
8990 T1=TIMEDATE
9000 IF A4=1 THEN GOTO T6bypass
9010 IF DROUND(T1-T0,3))=T6 THEN
9020 OUTPUT 709;"DC10,1"
9030 OUTPUT 709;"DC10,0"
9040 A4=1
9050 END IF
9060 T6bypass: !
9070 GOTO 9080 !* THIS NUMBER WILL BE CHANGED WHEN RENUMBER.
9080 RETURN
9090 Shutdown: !
9100 OFF CYCLE
9110 Jmax=J-1
9120 PRINT USING "@ "
9130 PRINT " TEST COMPLETE, TURN OFF 'MAIN-AIR', AND TURN OFF 'HEATER
CASES'"
9140 BEEP

```



```

9710 END IF
9720 IF I=6 AND Ff=1 THEN
9730   Vf=In(J,I)
9740   F=(Vf-Vf0)*Kf
9750 END IF
9760 IF I=6 AND Ff=0 THEN
9770   F=0
9780 END IF
9790 IF I=7 THEN
9800   Vpif=In(J,I)
9810   Pif=(Vpif-Vpif0)*Kpif
9820   IF Pif=(Ph+20) THEN
9830     Pif=0.
9840   END IF
9850 END IF
9860 IF I=8 THEN
9870   Vpp=In(J,I)
9880   Pp=(Vpp-Vpp0)*Kpp+Pbar
9890   IF Pp=(Ph+20) THEN
9900     Pp=0.
9910   END IF
9920 END IF
9930 IF I=9 THEN
9940   Volts=In(J,I)
9950   GOSUB Tcalc
9960   Ti=T
9970 END IF
9980 IF I=10 THEN
9990   Volts=In(J,I)
10000   GOSUB Tcalc
10010   Ta=T
10020 END IF
10030 IF I=11 AND Ht=1. THEN
10040   Volts=In(J,I)
10050   GOSUB Tcalc
10060   Thf=T
10070 END IF
10080 IF I=12 AND Ht=1. THEN
10090   Volts=In(J,I)
10100   GOSUB Tcalc
10110   Tho=T
10120 END IF
10130 IF I=13 THEN
10140   Volts=In(J,I)
10150   GOSUB Tcalc
10160   Tif=T
10170 END IF
10180 IF I=14 THEN
10190   Volts=In(J,I)
10200   GOSUB Tcalc
10210   Tp=T
10220 END IF
10230 NEXT I
10240 T=J/2
10250 Mair=Kair*Cdair*Pa*.7854*(Dairchoke^2)/(Ta^.5)
10260 Mhf=Kmf*Cdhf*Phf*.7854*(Dhfchoke^2)/(Thf^.5)
10270 Mho=Kmo*Cdho*Pho*.7854*(Dhochoke^2)/(Tho^.5)
10280 Mif=Kmf*Cdif*Pif*.7854*(Difchoke^2)/(Tif^.5)
10290 Mo=Kmo*Cdp*Pp*.7854*(Dpchoke^2)/(Tp^.5)
10300 PRINT USING "2X,DD,DD,3X,DD,DDD,4(3X,D.DDDDD),5(3X,DDDD.DD)";T,Mair,Mhf,Mi
10310 he,Mif,Mo,Ti,F,Pc,Ph,Ta
10320 NEXT J
10330 PRINTER IS 1
10340 PRINT USING "E"
10350 INPUT "DO YOU WANT TO MAKE POST-RUN AIR CALCULATION? (Y/N)",Yy$
10360 IF Yy$="Y" THEN Ko=1
10370 IF Yy$="N" THEN GOTO Finish
10370 GOTO Paset ! TO CALCULATE THE EFFECTIVE THROAT DIAMETER

```

10380 Finish: !
10390 PRINT "DATA OUTPUT IS COMPLETE"
10400 DISP "SECURE TEST CELL !!!"
10410 LOCAL 709 ! RETURN LOCAL MODE
10420 END

LIST OF REFERENCES

1. Grant Allan Begley, Jr., An Experimental Investigation of The Combustion Behavior Of Solid Fuel Ramjets, M.S Thesis, Naval Postgraduate School, Monterey California, December 1982.
2. Winston Elliot Scott, An Investigation Of The Reacting And Non-reacting Flow Characteristics Of Solid Fuel Ramjets, M.S Thesis, Naval Postgraduate School, Monterey, California, September 1980

INITIAL DISTRIBUTION LIST

	No.	Copies
1. Defense Technical Information Center Cameron Station Alexandria, Virginia 22314		2
2. Library, Code 0142 Naval Postgraduate School Monterey, California, 93943		2
3. Department Chairman, Code 67 Department Of Aeronautics Naval Postgraduate School Monterey, California 93943		2
4. Professor D. W. Netzer, Code 67Nt Department Of Aeronautics Naval Postgraduate School Monterey, California 93943		2
5. Korea Army H.Q G-3 P.O Box 4 Yong San Ku Yong San Dong, Seoul, KOREA 140		2
6. Ko, Bog Nam 315 Su-san-ry Okueub Okukun Chun-Buk, KOREA 511-10		2
7. Kang, Chang Koo Choong-Nam Cheon-An City Won-seong-dong 556-21 Republic of Korea 360		1
8. Library Korea Military Academy Gong-reung-dong Do-bong-ku Seoul Korea 130-09		1
9. Central Library 134 Yon-hee-dong Seo-dai-moon-ku Yon Sei University Seoul Korea 121		1
10. Kim, Young Joo SMC 2364 NPGS Monterey California 93943		1
11. A. Kertadijaya SMC 2848 NPGS Monterey, California 93943		1

- | | | |
|-----|--|---|
| 12. | Lee, Cheong Koo
434 Kuan-jeo-dong, Choong-Gu
Tea-jeon, Republic of Korea | 1 |
| 13. | Lee, Jang Hun
SMC 1366 NPS
Monterey, CA 93943 | 1 |
| 14. | Yim, Chang Ho
SMC 2425 NPS
Monterey, CA 93943 | 1 |
| 15. | Joo, Kyung Ro
SMC 2707 NPS
Monterey, CA 93943 | 1 |

END

FILMED

7-85

DTIC